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RECENT CONTRIBUTIONS TO THE GEOLOGY OF THE MICHIGAN COPPER DISTRICT.[1]

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ABSTRACT.

Developments not previously published in geological studies of the Michigan copper district by the Calumet and Hecla Geological Department

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are presented. The earlier estimates of the thickness of the basic lava and sedimentary parts of the Keweenawan section, recently disputed, have been substantially confirmed in many explorations. From time to time the question has been raised as to whether the Greenstone may not be a sill rather than a flow. Recent evidence confirms its identification as a flow. Some of the features of the known lodes as revealed by underground studies are discussed.

Numerous attempts have been made to relate the known deposits to broad geological features and structures and to group them into various sorts of patterns. The results of some of these studies are given.

Arguments are presented which indicate that the deep channels along which the copper depositing solutions ascended to form the known conglomerate and amygdaloid ore bodies were in most if not all cases, conglomerates interbedded in the flow series.

Calumet and Hecla geologists still believe that the copper deposits are epigenetic, having been formed by the activity of ascending hydrothermal solutions which brought in the copper from some source in depth. The suggestion that the source of the copper is the basic trap flows themselves is discussed and discarded as unlikely. The possibility that the deposits are of syngenetic origin is likewise examined and discarded as unlikely.

The various incentives from a geological point of view for continued exploration in the district are discussed. While there can be no positive assurance that undiscovered deposits do exist, the chances are in favor of that conclusion. The prevailing cover of glacial drift could effectually conceal such deposits. The tendency for conglomerate ore shoots to have short lengths along the strike near surface and the erratic distribution of copper in the amygdaloid deposits would make it possible or even likely that the widely spaced drill holes over much of the district would have failed to reveal them.

INTRODUCTION.

In the fall of 1919, the Calumet and Hecla Mining Company started a geological investigation of the Michigan copper district (herein commonly referred to as the "C. & H. Special Survey") under the supervision of L. C. Graton. Working with him was a group, the regular members of which were B. S. Butler, Charles Palache, T. M. Broderick, C. D. Hohl, Alfred Wandke and Marie J. Scholz. Studies by this group continued until the spring of 1924, not only on Calumet and Hecla lands but on those of the other companies in the district who gave access to their information and properties. At the close of this period, Messrs. Broderick and Hohl joined the regular staff of Calumet and Hecla, and Mr. Butler rejoined the U. S. Geological Survey, with which he had formerly been associated. Mr. W. S. Burbank was then assigned by the survey to assist Mr. Butler, and for over a year Butler and Burbank were in the district assembling the Calumet and Hecla geological data and preparing it for publication by the Survey. They also completed odds and ends of field work, being assisted in most of these activities by Messrs. Broderick and Hohl. The final outcome of the work was the publication of Professional Paper 144, "The Copper Deposits of Michigan," and the continuation of geological studies by Calumet and Hecla in connection with its exploration.

The Survey acknowledges the dominant part played by Calumet and Hecla in making their report possible, in the following words,[2] "The Calumet and

[2] Butler, B. S., and Burbank, W. S., The copper deposits of Michigan, U. S. Geol. Surv. Prof. Pap. 144, p. 2, 1929.

Hecla Consolidated Copper Company made the outstanding contribution, starting the work, and paying for a large part of it; and without this cooperation the report by the Geological Survey would not have been undertaken. Whatever of usefulness comes to the district from this report should be largely credited to that company." It is a source of satisfaction that the Survey, after an interval of about twenty years, has recently decided to include this district among those deserving of their further attention, and a party has now been working here for over three years. They were assigned to the district originally to attempt to aid in production during the war, by detailed geological studies in some of the mines.

The accumulation of geological data by Calumet and Hecla has continued after the Survey left the district in 1925, up to the present time. Most of this material has not been of general interest and has therefore not been published, but several articles have been presented embodying contributions to the fields of economic geology and petrogeny. These are as follows:

T. M. Broderick, Zoning in Michigan copper deposits and its significance. ECON. GEOL. 24: 149–162; 311–326, 1929.

Fissure vein and lode relations in Michigan copper deposits. ECON. GEOL. 26: 840–856, 1931.

Differentiation in lavas of the Michigan Keweenawan. Bul. G. S. A. 46: 503–558, 1935.

T. M. Broderick and C. D. Hohl, Differentiation in traps and ore deposition. ECON. GEOL. 30: 301–312, 1935.

In addition, a summary of the results of the application of geophysical methods in the district was published under the folowing title and it appeared in time to be included in the Professional Paper.

T. M. Broderick and C. D. Hohl, Geophysical methods applied to exploration and geologic mapping in the Michigan copper district. ECON. GEOL. 23: 489–514, 1928.

Mr. L. M. Scofield was a member of the department from November, 1936, to August, 1943, and the value of his critical review of the existing geological theories and his suggestions of things worthy of trying out in the exploration, are acknowledged. Mr. H. N. Eidemiller has been a member of the department since January, 1936.

In the last decade of the company's continued geological research, ideas of varying merit have been fitted into and tried out in the exploration program. This would seem to be an appropriate time to discuss some of these developments and the modifications, changes and additions to fact and theory which have occurred in this period. It is practically impossible in a paper of this nature to present material in such a way that the reader unfamiliar with the earlier literature will be able to follow it with entire satisfaction and understanding but efforts have been made to make this presentation as independent as is consistent with clarity and space limitations. Where advisable, some of the earlier published material is reviewed. Most of the formation and geographic names will be found on Fig. 1 or on other figures in this paper. A few have been left out, but may be found on the maps of Professional Paper 144. Mr. Hohl is to be especially credited with the collection of much of the detailed

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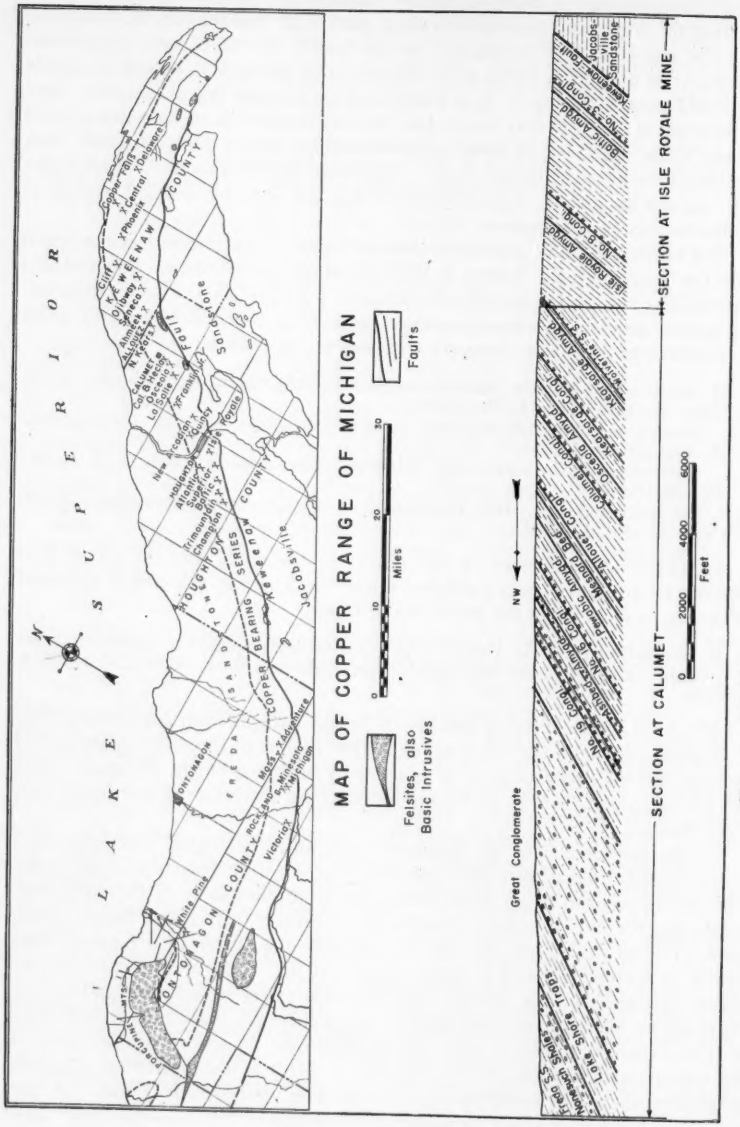
MAP OF COPPER RANGE OF MICHIGAN
Faults
Felsites, also Basic Intrusives
Miles
Feet
SECTION AT ISLE ROYALE MINE
SECTION AT CALUMET
Great Conglomerate
LAKE SUPERIOR
HOUGHTON COUNTY
KEWEENAW COUNTY
ONTONAGON COUNTY
COPPER BEARING SERIES
Jacobsville Sandstone
Kearsarge Conglomerate
Isle Royale Amygd.
No. 3 Conglomerate
Isle Royale Conglomerate
Isle Royale Amygdaloid
Isle Royale Lava Conglomerate
Osceola Amygdaloid
Osceola Conglomerate
Calumet Amygdaloid
Calumet Conglomerate
Allouez Amygdaloid
Allouez Conglomerate
No. 8 Conglomerate
Lake Shore Trap
Lake Shore Conglomerate
Portage Lake Lava Series
Keweenaw Point
Eagle River
Eagle Harbor
Central (Decisions)
Phoenix
Clifton
Ahmeek
Allouez
Calumet & Hecla
Laurium
Tamarack
Quincy
Hancock
Houghton
Portage Lake
Franklin
Boston
Pewabic
Baltic
Trimountain
Champion
Osceola
Kearsarge
Centennial
Wolverine
Isle Royale
Mohawk
Ahmeek
Allouez
Calumet & Hecla

information which is the foundation for studies of this sort and Mr. Eidemiller with the preparation of the illustrations.

GENERAL GEOLOGY.

Thickness of Keweenawan.—Much information concerning the thickness of the formations in a large part of the section in the Michigan copper district has been acquired in recent years. This is especially accurate for the areas in northern Houghton and Keweenaw Counties where diamond drilling has been

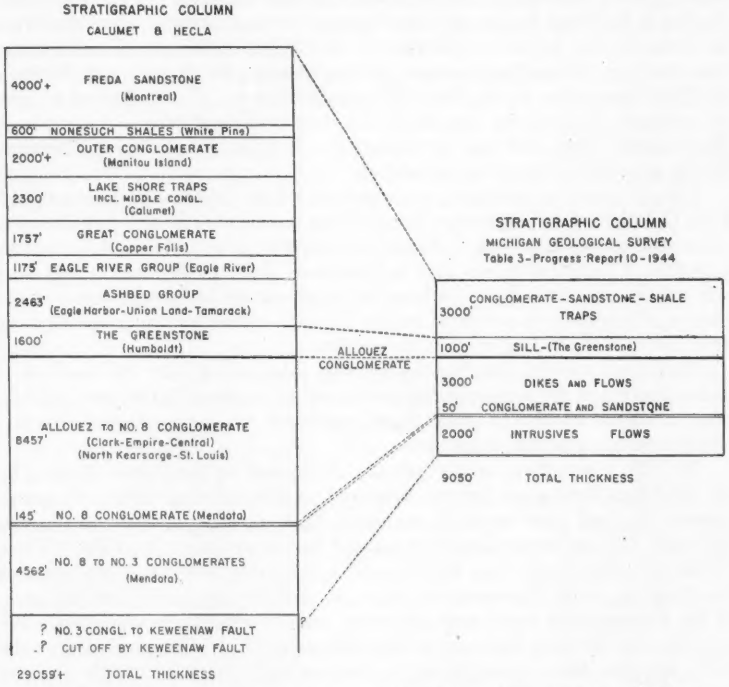
STRATIGRAPHIC COLUMN
CALUMET & HECLA
4000'+ FREDA SANDSTONE (Montreal)
600' NONESUCH SHALES (White Pine)
2000'+ OUTER CONGLOMERATE (Manitou Island)
2300' LAKE SHORE TRAPS INCL. MIDDLE CONGL. (Calumet)
1757' GREAT CONGLOMERATE (Copper Falls)
1175' EAGLE RIVER GROUP (Eagle River)
2463' ASHBED GROUP (Eagle Harbor-Union Land-Tamarack)
1600' THE GREENSTONE (Humboldt)
8457' ALLOUEZ TO NO. 8 CONGLOMERATE (Clark-Empire-Central) (North Kearsarge-St. Louis)
145' NO. 8 CONGLOMERATE (Mendota)
4562' NO. 8 TO NO. 3 CONGLOMERATES (Mendota)
? NO. 3 CONGL. TO KEWEENAW FAULT
? CUT OFF BY KEWEENAW FAULT
29059'+ TOTAL THICKNESS
ALLOUEZ CONGLOMERATE
STRATIGRAPHIC COLUMN
MICHIGAN GEOLOGICAL SURVEY
Table 3 - Progress Report 10 - 1944
3000' CONGLOMERATE - SANDSTONE - SHALE TRAPS
1000' SILL - (The Greenstone)
3000' DIKES AND FLOWS
50' CONGLOMERATE AND SANDSTONE
2000' INTRUSIVES FLOWS
9050' TOTAL THICKNESS

FIG. 2. Michigan copper district, stratigraphic column, basic extrusives and sediments.

carried on. In general, the thickness of the traps and sediments proves to be of the same order of magnitude as estimated by earlier geologists and accepted by the U. S. Geological Survey and until recently by the Michigan Geological Survey. Fig. 2, left hand column, shows the maximum thickness for various intervals in the trap and sediment portions of the section, according to the best data available. With the exception of the upper 6,000 feet (the Freda sandstone and Outer conglomerate) we have checked and modified earlier estimates

during the course of our own explorations. The measurements are all taken from sections within the limits of the copper district proper; except for those on the Freda sandstone and the Outer conglomerate, where sections at the Montreal river, near the Michigan-Wisconsin state boundary, and on Manitou Island, just off the end of Keweenaw Point, were used. It will be noted that the section should be increased by an unknown amount at the bottom, to include beds below No. 3 conglomerate which are known in the copper district only within the disturbed zone adjacent to the Keweenaw fault, and also to include the lowermost beds which are cut out by the fault. That some of the subdivisions of the Keweenawan section attain a greater thickness outside the copper district is indicated by the sections measured in such areas. Thus the Freda sandstone is said to have a thickness of 12,000 feet in Wisconsin and the section from the Allouez conglomerate to conglomerate No. 8, to have a thickness of 25,000 feet in the Black River, Wisconsin section. If it is desired to refer to estimates of thickness outside of the copper district, the bibliography in Professional Paper 144 may be consulted. Publications by Lane, Thwaites, Irving and others deal with the subject.

Careful work by Sandberg on a portion of the Minnesota Keweenawan, from Duluth to the Temperance River, shows in excess of 25,856 feet thickness of extrusives and sediments.[3] About ten per cent of this is acidic flows leaving a section of basic extrusives and sediments of about 23,000 feet. This does not include any of the great thickness of conglomerate in the upper part of the section, which from its presence on Isle Royal Island is known to exist on the north limb of the Lake Superior geosyncline.

Thus from careful observations on both sides of the lake, the basic lavas and sediments of the Keweenawan are known to be about 30,000 feet in thickness, a figure consistent with those published by earlier authorities and checked by many recent observations.

In 1929, a report on several seasons' field work in the copper district, by the Michigan Geological Survey, appeared.[4] After stating that by magnetic observations and other methods, numerous faults striking at a low angle with the traps and sediments had been located the report says (p. 157), "These 'Strike' or 'Slide' faults may have caused a surprising amount of repetition or 'doubling up' of the Keweenawan series, so that the supposed great thickness of the Keweenawan traps and sediments may be grossly exaggerated. We mention this because facts are accumulating, not only from our dip needle work but also from observations on the outcrop, which seemingly tend to verify this theory (held by A. E. Seaman and others) of considerable repetition. Presentation of these facts is, of course, beyond the scope of this paper."

Following this line of thought further, the State Survey recently published a chart showing in general where this "gross exaggeration" lies and naturally disagreeing radically with other estimates of Keweenawan thickness.[5] With-

[3] Sandberg, A. E., Section across Keweenawan lavas at Duluth, Minnesota. Bulletin G. S. A. 49: 828, 1938.

[4] Seaman, W. A., Geological and magnetic field work in the Keweenawan of the Michigan Copper Country. Lake Superior Mining Inst. Proc. 27: 155–159, 1929.

[5] Seaman, A. E., and Seaman, W. A., Geological column, Lake Superior region in general, Table 3 in "Strategic minerals investigations in Marquette and Baraga Counties." State of Michigan, Geological Survey Division, Progress Report No. 10, 1944.

out any supporting data or explanations it gives the thicknesses of the various subdivisions of the basic extrusive and sedimentary portions of the section as indicated on Fig. 2, right hand column.[6] The total Calumet and Hecla figure of 29,059+ feet is cut to 9,050 feet in the Seaman column.

This recent publication of the Michigan Survey carries the statement that "Thicknesses may vary as much as 50 per cent from figures specified." This is taken to mean that while the figures given for the various groups are the author's best estimates, they may be either too high or too low by as much as 50 per cent. Unless by coincidence his errors for these groups all lie in the same direction, they should substantially balance each other, some being too high and others too low and his total of 9,050 feet would be correspondingly unaffected.

For many years, geologists have recognized and mapped faults in the district. However, the many thousands of feet of diamond drilling done by this company and others has enabled very definite and accurate stratigraphic columns to be built up, especially from Painesdale to the end of the Point. This department can set up drill locations in a great part of this area and predict within a few feet the depth at which the holes will strike key horizons. If faults had caused repetitions on the scale assumed by Seaman, this could not be done. Furthermore, such faults would be detected in the drilling by the occurrences of broken ground or gouges, or if the gouge were ground out and not recovered there would nevertheless be sudden changes in ophite grain size on opposite sides of the fault plane or other stratigraphic anomalies would be present. Occasionally such occurrences are recognized and proper allowance made for them, but in the great majority of drill sections, the record is unbroken and the key horizons are found precisely as predicted from the column as determined by projection from adjacent sections.

In this connection the bedding plane "slides" which occur on the tops of some of the conglomerates should be mentioned. A broken zone, often a foot or more in thickness with abundant gouge, is commonly found along the contact between the conglomerate and the overlying flow. The Allouez, Houghton and Kearsarge conglomerates especially show this feature. Obviously movement has occurred along such horizons. In the scores of intersections of such horizons known to the writers, in no case has the slide been observed to cross the bedding nor to result in a "doubling up" of the conglomerate itself. Such movements are therefore interpreted as being purely displacements between and parallel to the beds, taking place during the tilting of the formations, along the relatively smooth planes at the tops of the conglomerates.

In the Minnesota work by Sandberg, he had in mind the possibility of

[6] We recognize that there are acidic flows in the section in certain areas, and that insofar as they are not contemporaneous with formations whose thickness is already included in the column, their thickness should be added to both columns in order to get a figure for the total column. We also recognize that there are intrusives such as the Mt. Bohemia gabbro and the Bare Hills felsite, but any estimate of their thickness has no place in the stratigraphic column under discussion. The Seaman column as shown includes unspecified thicknesses of "dikes" and "intrusives" which we cannot separate for the intended comparison of the thicknesses of the basic lavas and sediments in the two columns. The lowermost beds of the Keweenawan, cut out by the Keweenaw fault, should be added to both sections if their thickness were known.

there being repetition of the beds by faulting. After giving consideration to the matter he said "Study of the flow sequence and careful field search do not indicate that an appreciable duplication of beds, if any, had resulted from faulting." [7] The fact that the true thickness of the traps and sediments on the north limb of the syncline, as determined after the possibility of repetition by faulting has been considered and eliminated, has the same order of magnitude as that on the Michigan limb, after a similar elimination of the possibility of faulting repetition, affords mutual corroboration of the correctness of the estimates.

Great caution should be used in the interpretation in terms of structure of magnetic data such as are obtained by the use of the dip needle. Anyone attempting interpretations of such data from the Michigan Keweenawan without having acquired a familiarity with the amazingly erratic behavior of the lava flows is likely to come to some very erroneous conclusions.

We know from our study of many cross sections, that although in parts of the section individual flows have great persistence along the strike, maintaining a fairly uniform thickness, in other parts of the section they are subject to great variations. A single flow, several hundred feet in thickness, may in a comparatively short distance, be replaced by numerous thin flows. Regardless of such irregularities, the distance between the key horizons, above and below, maintains a decided consistency. In general, the strong magnetic lines are found over the thick flows, and if one were following a discontinuous flow along the strike, by dip needle readings, the strong anomaly would naturally be cut off where the flow ended or narrowed sharply. Those who fail to recognize such irregularities in flow thickness would be tempted to explain the sudden disappearance of a strong magnetic line by a fault, especially if a new line should start in a few hundred feet across the strike from where the old line played out.

In Fig. 2, left column, the thicknesses of various stratigraphic intervals in the Michigan Keweenawan have been given in detail. The data upon which a large part of our tabulation is based have been rechecked many times in diamond drilling and in underground crosscuts. There would seem to be a heavy burden of proof on anyone disputing its substantial accuracy.

Location of Volcanic Vents.—The Calumet and Hecla Special Survey favored the idea that the volcanic vents from which the flows were extruded were fissures located in what is now the Lake Superior basin, and that the sources of the sediments were likewise down the present dip. The downward thickening of sediments, their cross bedding, the thickening of the section down dip, the inclination and bending of "pipe" amygdules all gave support to this conclusion. It had been developed earlier especially by Hotchkiss and as pointed out by Sandberg, had been favorably regarded by Coleman and Tanton still earlier. More recently Sandberg in his studies of the details of the lavas and sediments on the Minnesota shore of Lake Superior, made many observations bearing on the determination of the direction from which the lavas and sediments came and his conclusion was that their source was down

[7] Sandberg, A. E., op. cit.

the present dip.[8] Thus the results of studies on both limbs of the Lake Superior syncline are again mutually corroborative.

The Greenstone.—One of the conspicuous topographic features of Keweenaw County is the cliff which runs along for many miles marking the base of an ophite known as the Greenstone, just above the Allouez conglomerate. It has been thought by some that instead of being one of the lava flows of the series, it was later intruded as a sill.[9, 10] Its great thickness and the advanced stage to which its internal differentiation has been carried are characteristics which make it necessary to consider that possibility. The Calumet and Hecla geologists have always taken the position, as expressed by others in the earlier publications of the Michigan Geological Survey, that it is a flow. As the study of the district has progressed, this belief has been strengthened. Some of the arguments bearing on the subject are as follows:

1. THICKNESS. Previously published records mention a maximum known thickness of 1,300 feet. Recent explorations indicate that it reaches a thickness of 1,600 feet between Ojibway and Central. While this may not be its maximum thickness it nevertheless is more than that of any known flow in the district. However, flows more than 500 feet in thickness are not uncommon, and one ophitic flow, immediately above the Bohemia conglomerate in the Central section, approaches 1,000 feet in thickness in some of the explorations. Unless by coincidence these explorations encountered the place of maximum thickness, it is even thicker than that. Therefore, from the standpoint of thickness it does not seem necessary to regard the Greenstone as having a different origin from flows which are known to approach 1,000 feet in thickness.

2. DIFFERENTIATION. It is strongly differentiated as compared with the thinner flows. For this reason it was selected as one of the two studied in Broderick's paper on "Differentiation in Lavas of the Michigan Keweenawan." The other flow studied in similar detail was only 164.5 feet in thickness where the samples were taken. Nevertheless, while the differentiation in the thinner flow was less complete, as would be expected, it was of the same type as that exhibited by the Greenstone.

The 1,000 foot thick flow above the Bohemia conglomerate mentioned above, is also an ophite, and in the upper half it has the same type of pegmatitic or "doleritic" layers as shown in the same horizon by the Greenstone. These pegmatitic layers are developed in many of the thicker ophites of the district.

This same 1,000 foot flow also shows the same dense fine grained phases near both top and bottom contacts as does the Greenstone.

Therefore, it may be said that the differentiation shown by the Greenstone is the same in kind as that shown by other thicker ophites of the district. It differs only, so far as known, in having been carried to a more advanced stage, as would be expected because of its greater thickness.

[8] Sandberg, A. E., op. cit., pp. 818–821.

[9] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior Region, U. S. Geol. Survey Mon. 52, p. 381, 1911.

[10] Seaman, A. E., and Seaman, W. A., op. cit.

3. AMYGDALOIDAL TOP. The Greenstone has an amygdaloidal top, in most places of a thin cellular type. The other exceptionally thick ophites likewise tend to have cellular amygdaloidal tops. Therefore, the Greenstone resembles the other flows of its class in this respect.[11]

4. POSITION IN FLOW CYCLES. It has been pointed out that the flow immediately following each of certain of the extensive and best known sediments is an ophite, exceptionally thick, doleritic and in some cases containing plagioclase phenocrysts. Examples of these are flows following the conglomerates Nos. 3, 8, 12 and the Wolverine sandstone. The Greenstone flow has all of these characteristics and lies immediately above the Allouez conglomerate No. 15. Thus it makes another addition to the group and takes a consistent place among the flows which occupy a definite place in the cycles.[12]

5. RELATIONS TO NEARBY FORMATIONS. Immediately beneath the Greenstone is the Allouez conglomerate. This is true over its many miles of extent, the occasional exception being only an apparent one where in a few local spots thin preliminary gushes of the Greenstone are found between the conglomerate and the main flow itself. No places have been found where beds normally above or below the Greenstone are found below or above respectively as would be the case if it cut across the beds as an intrusive. In other words, the Allouez conglomerate horizon, at the top of the well known section including the Houghton and Calumet conglomerates at their proper intervals, is always just below the Greenstone, never above. Similarly, the section including No. 16 conglomerate and the Ashbed is always above, never below.

In no place have apophyses from the Greenstone, intruding the adjacent beds, been found.

There are now enough intersections of the top of the Greenstone to give a clue as to how the rest of the section accommodates itself to the extraordinary thickness of the Greenstone (Fig. 3). Toward the southwest where the Greenstone is 200 feet thick, there is a thickness of 1,100 feet of flows between conglomerate 16 and the top of the Greenstone. Further northeast, where the Greenstone becomes 1,600 feet thick, this group of overlying flows thins down to 250 feet, which takes care of 850 feet of the 1,400 feet increase in Greenstone thickness. The inference is that the Greenstone remained as an eminence above the general elevation at least during the accumulation of the 850 feet of lavas on its southwestern flank. The section between conglomerates 16 and 17 thins from 600 to 470 feet from the flanks to the section of maximum Greenstone thickness, suggesting that there was still an eminence above the Greenstone crest during the deposition of those beds.

Perhaps some of the remaining thickness of about 400 feet of Greenstone thickening was accounted for by a sag in the underlying section. Fig. 4 shows conditions according to the assumption that the surface during the deposition

[11] The relationship of type and thickness of amygdaloid top and thickness of flow needs further study. Many comparatively thin flows have thick fragmental tops. On the other hand the very thick flows tend to have cellular amygdaloidal tops, in some cases only a few feet thick. Perhaps the distance from the source, in conjunction with the flow thickness, is a determining factor.

[12] Broderick, T. M., Differentiation in lavas of the Michigan Keweenawan. Bull. Geol. Soc. Am. 46: 553, 1935.

of No. 17 conglomerate was a plane, and that a part of the remaining Greenstone thickness, unaccounted for in the filling-in on the flanks by later lavas, was reduced in amount either subsequently or parri passu by a sag in the section.

The thicknesses of the felsitic material brought in and deposited in the horizons of Nos. 16 and 17 conglomerates, with relationship to the lenticular

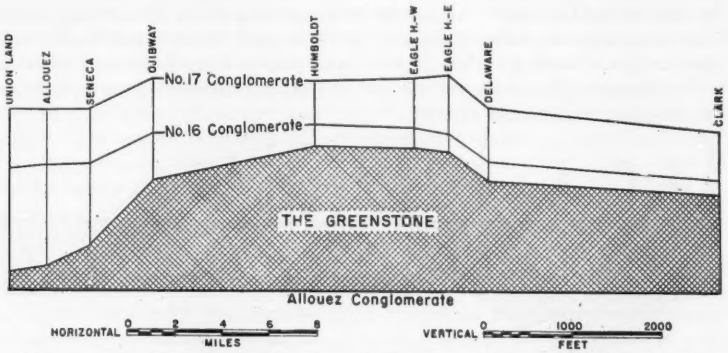

FIG. 3. Stratigraphic sections through the Greenstone and overlying beds, Allouez conglomerate as base.

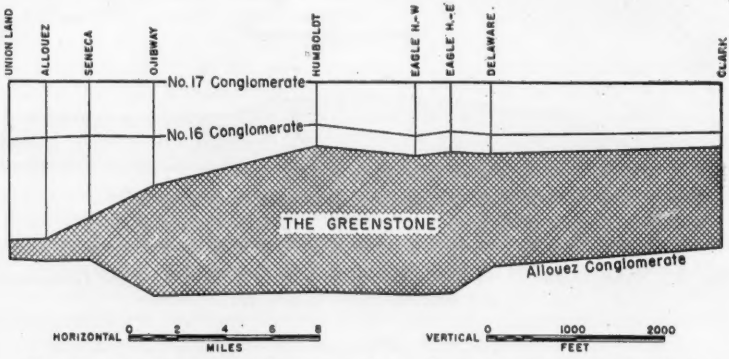

FIG. 4. Stratigraphic sections through the Greenstone and overlying beds, No. 17 conglomerate as base.

longitudinal section of the Greenstone flow, is shown in Fig. 5. The felsitic material is found above the flanks of the Greenstone flow. Over the thick part it is almost lacking, suggesting that that region still stood up too high to allow foreign material to be deposited on it. Over the thicker Greenstone area these horizons are marked chiefly by the remnants of eroded and rearranged local material known as a type of scoriaceous amygdaloid. As shown

in Fig. 5, the deposits of the local products of weathering and erosion are also much thicker on the Greenstone flanks, suggesting that they were washed down from the more elevated area above the region of maximum Greenstone thickness.

Differentiation of Keweenawan Lavas.—Little has been done to add to the study as presented in the paper "Differentiation in Lavas of the Michigan Keweenawan." A discussion of certain phases of this paper was presented by Sandell and Goldich.[13] Broderick emphasized gaseous transfer as a dominant process in the differentiation of the flows and Sandell and Goldich emphasize crystal settling. Any reader interested in the subject in general or in the Broderick paper should not fail to read the excellent presentation and discussion by Sandell and Goldich.

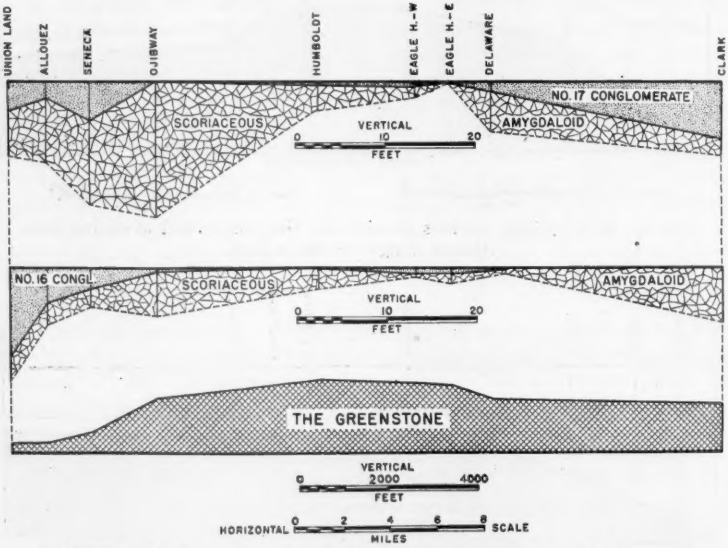

FIG. 5. Stratigraphic sections showing variations in thickness of the Greenstone and conglomerates 16 and 17.

INTERNAL FEATURES OF ORE BODIES.

Introduction.—In most mining districts geological studies are made for two purposes. One is to help in the mining of known ore bodies, and the other is to work out rational plans of exploration for new ones. A study of the details of the known ore bodies is essential for the accomplishment of either purpose. Therefore, in the Michigan copper district much attention has been given to the details of the deposits as seen in the accessible workings of the mines.

[13] Sandell, Ernest B., and Goldich, Samuel S., The rarer metallic constituents of some American igneous rocks. Jour. Geol. 51: 99–115, 167–189, 1943.

So far, in the mines operated by Calumet and Hecla, the geological work helpful in the control of operations is of a type which can in most cases be handled by the operating organization itself rather than by the geologists. Thus, displacement by faulting presents practically no problem requiring the attention of the geologists. Faults are infrequent, and the great majority of those which do occur have offsets which are less than the lode thickness. The rare faults which have greater offsets are so regular in their behavior that their effect can be predicted by the operators in the new levels as they are opened.

In most districts, sampling of the openings is regular practice and may be the duty of the geological staff. In Michigan, sampling of the ordinary type is not done as the copper is too erratically distributed. The substitutes are the visual estimates of the operators and the periodic returns from the mill and smelter. In neither of these is the service of the geologist ordinarily required. Therefore, inasmuch as the simplest type of geological observation (such as the distinction between the lode, either conglomerate or amygdaloid, and the footwall and hanging wall traps), satisfies the requirements of the operators, they perform it themselves, and the geologist directs his attention to the attempt to gather some clue from the known deposits which will aid in finding others.

This examination has included such studies as the search for diagnostic minerals, elements, rock alteration, structures, in fact for any feature or characteristic peculiar to the copper bearing lodes which is more widespread or more uniformly distributed than the copper itself. Such a peculiarity might serve to direct attention to certain specific amygdaloids or conglomerates encountered in diamond drilling regardless of their failure to show attractive amounts of copper in the core itself. So far practically nothing of the sort which would be useful has been recognized. The properties of the copper-bearing lodes are almost identical with those of the barren lodes.

Presence of Copper.—Even the presence of copper itself in a drill core is viewed with caution. Stray solutions have deposited copper in amygdaloids, conglomerates and fissures all over the district and in all parts of the Keweenawan section. In fact, attractive specimens and even occasional masses of copper hundreds of pounds in weight have been found around the entire circumference of Lake Superior, wherever the Keweenawan outcrops.

Physical Character.—The physical character of an amygdaloid is of little significance in appraising its possibilities. While it is true that the commercial amygdaloids are dominantly of the fragmental type, there are many noncommercial amygdaloids of identical character, and on the other hand, all of the commercial lodes have tight, cellular and impermeable ash-filled stretches in them which are commonly unmineralized and are left unstoped.

Gangue Minerals.—The gangue minerals of commercial and noncommercial lodes are identical, so far as is now known. There is a feeling that the commercial deposits have a greater variety of minerals than the noncommercial lodes, but this may only be an apparent rather than a real difference, due to the fact that the commercial lodes with their abundant mine openings offer a greater opportunity for study and the building up of a more complete list of minerals. Perhaps the occurrence of red feldspar in a felsite conglomerate

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would be a real clue to important mineralization inasmuch as it is fairly common in the Calumet conglomerate ore body and almost if not entirely lacking in other felsite conglomerates. Those without red feldspar include even the more weakly mineralized patches on other conglomerates, such as on the Allouez where mined at Franklin Jr., Allouez and Delaware, on the Kearsarge conglomerate near Phoenix, and on the present exploration in the Houghton conglomerate at No. 3 Allouez. Certainly the relative abundance of this mineral in the great Calumet conglomerate ore body and its absence in the felsitic material of other conglomerates, even where weakly mineralized, would lead us to regard its occurrence in another conglomerate with interest. However, red feldspar in amygdaloids seems to have little significance as an accompaniment of copper since it is fairly abundant in both commercial and barren amygdaloids. Most of the datolite seen has been in commercial amygdaloids and its occurrence in a drill core arouses a mild degree of interest. It is probably of little use as a guide to copper, although the fact that it may mean the addition of boron might encourage the idea that copper would likewise be added in the same environment.

Rock Alteration.—None of the various types of rock alteration seen in the copper-bearing lodes seems to be especially restricted to them. Thus epidotization, silicification, chloritization, prehnitization and others are all found in nonmineralized lodes as well as in the mineralized ones. The alteration which involves reduction of the ferric iron of the lodes, with its removal or fixation in chlorite, is of some use in exploration, although it is felt that if the resultant bleaching were an accompaniment of copper in a given case, the copper would show itself also. There is also alteration of this same general type which is not associated with copper. Altogether, rock alteration types thus far recognized do not seem to be of much use as guides in exploration.

Chemical Properties of Lodes.—Attempts to discover some chemical property peculiar to the commercial lodes have not met with success. All of the common rock types of the district contain copper deposits of importance. These include conglomerate, amygdaloid, sandstone and shale. Copper bearing fissures may have masses of metal in and near them where they cross trap and felsites. The feeling expressed in recent years that the high ferric iron content of the amygdaloids and conglomerates through which the solutions travelled in their upward course accounts for the copper being in the native state, is still shared by us. However, the occurrence of great masses of copper along fissures in the midst of dense unoxidized trap indicates that the precipitation of the metal may be delayed, taking place at a distance from the ferric iron environment which exerted the oxidizing effect. At any rate there is no common rock in the district which may not be the ultimate host of commercial copper, and there are many barren amygdaloids and conglomerates having as high a ferric iron content as those containing ore bodies, in all parts of the Keweenawan, and all around Lake Superior.

Internal Solution Channels of Lodes.—Assuming that the copper was deposited by ascending solutions, the ore shoots in general must lie in a permeable environment which must be a part of a continuously permeable channel from source to an eroded outlet far above the present surface. The various features

in the lodes, especially in the amygdaloids, which affect the channels of permeability, constitute local ore shoot controls which appear very complicated. The so-called fragmental amygdaloids are made up dominantly of piles of amygdaloid fragments, of varying thickness and shape. These piles may cover large areas of simple shape many hundreds of feet in diameter, or may lie in irregular branching areas, or may be in parallel bars, thousands of feet in length. These variously shaped areas of fragmental lode are interrupted or separated in irregular fashion by areas of thin, cellular lode. The Osceola amygdaloid is an example of the simplest combination of lode types, and of the control which they exercise on copper occurrence. The relatively permeable through-going areas of fragmental lode got the copper, and the long raking bars of relatively impermeable, thin, cellular lode did not.[14]

Most of the other amygdaloid lodes are not as simple. Various complexities in the internal lode pattern occur which result in complexities in the copper distribution. In some of the lodes there are areas of favorable amygdaloid which have practically no copper in them. Such puzzling occurrences are probably due to the areas so affected being isolated or in embayments out of the channels of solution flow. Where the lode lies in an area of disturbance, resulting in many fractures of varying directions, the complexities may become especially confusing. While the amygdaloid itself is the main channel for solutions, the fissure intersections afford local channels of high permeability, allowing solutions to bridge across the impermeable areas separating the permeable ones. Such local controls of the copper distribution are likely to be misinterpreted. Fissures of this sort did not bring the solutions from some outside channel *into* the lode; they merely are a modifying and complicating element in the lode permeability system itself. They do in many cases, if they are persistent, allow some of the solutions to leak out and deposit copper locally in distant amygdaloids, especially in the hanging wall of the main deposit. The various relations of lodes and fissures have been discussed elsewhere.[15] The point being made here is that a study of the numerous fissures in the Kearsarge lode, for instance, might lead to an erroneous idea of their functions and importance. Such an impression would be corrected if access could still be had to the great Calumet conglomerate ore body with its almost entire lack of intersecting fissures.

The presence of patches and areas of fragmental amygdaloid in which the matrix of the fragments is a fine grained ash or mud, complicates the ore pattern. Several of these, roughly circular up to 1,500 feet in diameter, were mapped on the Osceola lode. With one exception they were practically barren of copper. What their origin was is not certain. On entering these areas along drifts passing into them from the surrounding normal lode, the mud first appears on the footwall side of the drift, nearest the bottom of the fragmental covering of the flow. It gradually works across the entire thickness of the lode. This suggests that these areas were depressions on the flow top while it was still horizontal, and that the mud might have been washed in from the surrounding surface before the next flow covered it.

[14] Butler, B. S., and Burbank, W. S., op. cit., p. 192 and Plate 39.

[15] Broderick, T. M., Fissure vein and lode relations in Michigan copper deposits. ECON. GEOL. 26: 840–856, 1931.

The most bewildering and from the standpoint of mining the most serious complications in ore distribution occur in lodes of a branching, multiple or compound character. The Calumet conglomerate was ideally simple and the Kearsarge amygdaloid almost equally so. The ore body occupies a definite position betwen the hanging and footwall traps. In places however, the Kearsarge flow sent out "squirts" which formed "blisters" on top of the main flow. Drifts following the hanging wall of the Kearsarge lode occasionally entered tight, unfavorable lode, the position of which when surveyed was found to be in the hanging wall of the normal position of the drift. Such openings had gotten off on amygdaloids along the tops of the "blisters." These experiences were never especially serious and are now very rare on the Kearsarge lode.

There are places in the series where the flows instead of being relatively thick and persistent as individuals between similar thick persistant flows, are discontinuous, with rapid changes in thickness, the individual flows ending and merging with others. Under such conditions, correlations between adjacent sections even only 100 feet apart, are impossible. A drift starting on one amygdaloid may get off on another one taking it a hundred or more feet away from the average strike line within a distance of only a few hundred feet. Where copper occurs in such a group of amygdaloids, mining is a very difficult problem. The Quincy mine has had to cope with such problems throughout its history. In recent years it has made a considerable production from sections of lodes not mined in earlier days. The Evergreen series of lodes in Ontonagon County is of a similar character. There the lode complexities of all types have prevented profitable operations in spite of what would be a fair copper content if the mineralization were confined to one or two lodes of a more regular character. It is possible that in the mining of such complicated lodes, the employment of a geologist to make systematic observations and studies of a character which the operators probably could not undertake themselves, might have proved profitable.

Solution Inlets and Outlets.—The location of the solution inlets into the lodes in depth and the outlets above the present erosion surface were of course major determining factors for the location of the ore bodies. If the lode were homogeneous over a large area between these points, the axis of the course of the solutions would be a straight line connecting them. However, the various local features mentioned above, such as thick and thin lode patterns, ashy areas, and fissure intersections, cause the lode permeability system to be far from homogeneous. Nevertheless a consistency in the trend of the ore shoots for thousands of feet in depth does give the most acceptable clue as to the direction down dip of the location of the inlet of solutions into the lodes. Thus the inlet into the Baltic lode would seem to be toward the south, in Champion, rather than to the north in the Trimountain and Baltic mines, since in the latter the ore bodies bottomed at shallower depths. In the Isle Royale mine the ore shoot thus far seems to extend straight down the dip. In Quincy the tendency is to pitch to the north, as is also the case with the Kearsarge ore body. The trend of the Osceola is to the south in depth (Fig. 6).

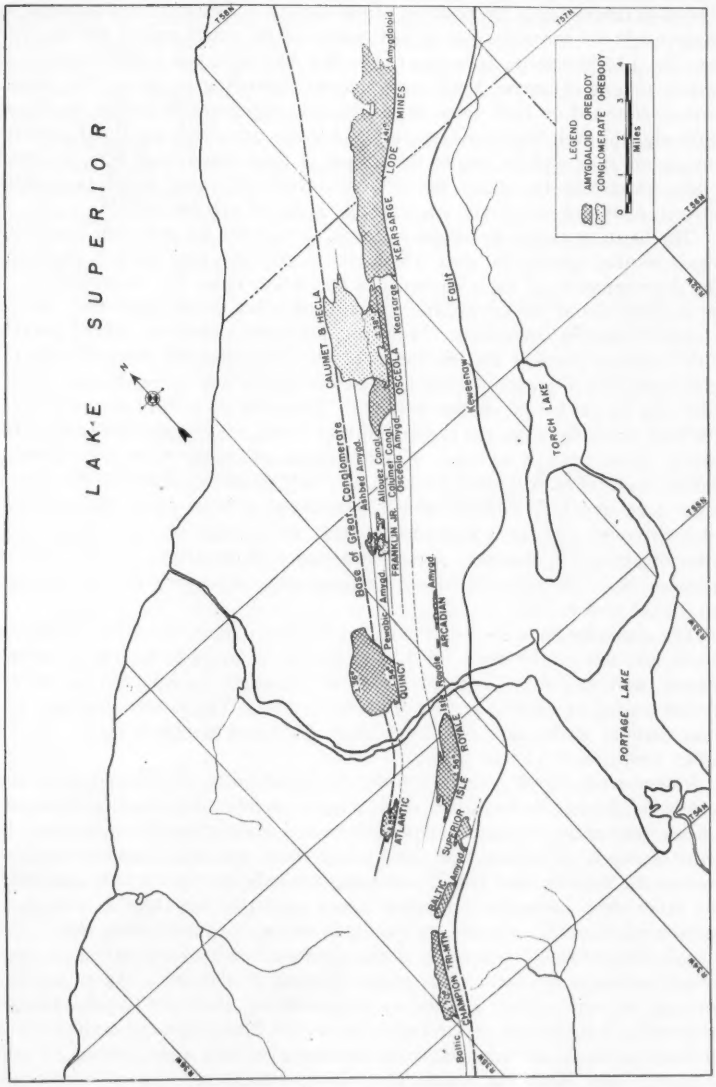

FIG. 6. Michigan copper district, map of major ore bodies.

The location of solution outlets seems to have exercised an important control in determining the position of ore shoots. Thus in the Calumet conglomerate,[16] the concentration of high values at the south end of the ore body near No. 12 Shaft seems to be due to the fact that there was in that area a long narrow tongue of coarse, thick conglomerate extending up above the present surface, confined on both sides by a relatively impermeable shaley sandstone. Similarly, the rich South Kearsarge-Wolverine ore shoot on the Kearsarge amygdaloid may well be due to the salient of thick fragmental lode, in which it lies, extending up above the present surface, forming a solution outlet between confining relatively impermeable areas of cellular lode.[17]

The location of the directions of inlets and outlets for solutions is of little help in mining operations, since it is pretty largely of a post-mortem character. The determination of these elements is dependent upon the determination of the position of the ore shoots, and this in turn is not known until they are developed in mining operations. However, the more closely the likely position of the solution inlets of the ore bodies can be estimated, the more reliable the deductions affecting explorations for new ore bodies will be, insofar as exploration may be guided by district patterns. Thus the pattern of the ore shoots at a level one mile below the present surface is much more significant than the pattern at the present surface. For the same reason the pattern of solution channels two miles deep would be still more significant in deducing the nature of the deep structural controls which determined at what points the solutions left a batholith roof, or a longitudinal fault, or a series of cross faults, or a series of permeable channels, caused by tongues of intrusives, to enter one of the many favorable amygdaloids or conglomerates, depositing the ore on their way to the outlets.

The main clue as to the location of the solution inlets is the trend of the ore shoots, and this can be determined by inspection of maps as well as by underground examinations. Corroborative evidence might be afforded by underground studies of mineral zoning, or arsenic ratio. The nearer the main solution channel or the axis of the ore body, the more abundant should be the higher temperature gangue minerals.

Richness vs. Depth.—Little remains to be added to the discussion of the richness of the ore bodies with relationship to depth. The studies of zoning indicate that native copper is deposited over a wide temperature range. In terms of depth, we know that the Quincy mine was rich from the surface down to the bottom, over 10,000 feet along the lode and over a mile vertically. The other deep mines have become leaner in depth but there is reason to question whether this was due to the depth factor or to something else. The Osceola lode probably is as rich at the greatest depth of operations as near surface, although the rather flat southerly pitch of the ore shoot causes the workings to reach leaner ground at progressively shallower depths toward the north. A large part of the better ore of the Kearsarge ore body spreads out below a barrier of thin, relatively impermeable lode as in Allouez, North Kearsarge and Wolverine, with rich shoots extending upward apparently

[16] Butler, B. S., and Burbank, W. S., op. cit., Plate 38.
[17] Butler, B. S., and Burbank, W. S., op. cit., Plate 40.

where salients of permeable lode penetrated the barrier affording solution outlets as in South Kearsarge. Although the lode becomes leaner with distance in depth below the barrier, this cannot be ascribed to the depth factor, since the ore shoot does go deeper along its major depth axis in Ahmeek. The company map, published in Prof. Paper 144 as Plate 40, is of course now obsolete, but it shows what is referred to fairly well.

The deepest mines from a zonal standpoint, that is, those in which copper deposition seems to have taken place at a higher temperature than elsewhere in the district, are those on the Baltic lode. The mines on this lode, the Baltic, Trimountain and Champion, were shut down because of leaner ore in depth. A study of the bottoms of these mines suggests three possible causes for a decline in grade, as follows:

1. The lode itself is tight and unfavorable in depth. Lode of such a nature is poorly mineralized regardless of the depth at which it occurs.
2. There is a suggestion that in these mines on the Baltic lode and also on the Isle Royale, the lode was fed by a series of near strike fissures, steeper than the lode, which swing into it from the footwall side. It might be that as the workings down the lode pass one after another of these feeders, the copper content would become less.
3. Finally these mines might be truly bottomed in the sense that the bottom of the zone of copper deposition has been reached.

Just as deposits play out in depth and laterally, so they may decline in grade upward. From a study of mineral zoning there is a suggestion that the copper showings outcropping in the north end of the district, such as those on the Iroquois lode, or on the Calumet amygdaloid at Cliff, are well above the zone of greatest concentration. If such is the case, a gradual improvement in depth might be expected.

Zoning.—Practically nothing has been done to change the ideas presented on zoning in the copper deposits. They still seem to be essentially sound, but there is a good chance for future studies to amplify the work and change the details.

Conclusions.—In the mining of some of the less complicated lodes, the elementary geological observations of the operators themselves have been sufficient to accomplish efficient extraction. In other operations on more complicated lodes, the employment of a geologist to make more detailed observations and to carry on studies of a character which would lie outside the province of a strictly operating organization, might have proved profitable. From the standpoint of the geologist whose responsibility is the exploration for new deposits, the study of the known deposits leads him to a realization of the nature of the problem and especially the limitations of the various methods of exploration which he must use. These are treated later in this paper.

Furthermore, because the concealment of such a high proportion of the rock surface by glacial drift makes outcrop observations fragmentary, the study of the more tangible data afforded by underground openings and diamond drill cores becomes essential. Underground openings are in general, only temporarily accessible, and we are in full sympathy with the policy of the present U. S.

Geological Survey group in the painstaking studies which they are making of the available mine openings. It is our hope that such studies of the internal characteristics of the known ore bodies will throw some new light on the problem of the discovery of new deposits.

GEOLOGICAL RELATIONS AND PATTERNS OF ORE BODIES AS GUIDES TO EXPLORATION.

For a century, prospectors, miners and geologists have tried to formulate rules which could be used as guides to exploration in this district. In the early days after the Cliff fissure had been opened, the rule was to look for other fissure deposits in the same horizons, under the Greenstone flow. Later, when the first amygdaloid deposits were found, this gave another type to explore for. Still later, with the discovery of the outstanding deposit of the district in both size and richness, the Calumet conglomerate, all three types were recognized and sought. As time has gone on, various rules and guides for exploration have been conceived and attempts have been made to apply them. The principal suggestions of this type have been as follows:

1. From the time of discovery of the amygdaloid and conglomerate deposits up to the present, there has been a belief which will probably always persist, that the particular horizons in which the known deposits are found are the "lodes" of the district and that new deposits are to be found by locating and exploring these same horizons along the strike. Thus one may find shafts on the Kearsarge amygdaloid, the Calumet conglomerate and the other "lodes" many miles from the known ore bodies. Many million dollars have been spent on this basis without success. No single horizon to date has been found to have more than one commercial deposit. The fallacy in this theory of exploration is its failure to recognize that the essential reason for the localization of each ore body is that some local condition in depth allowed copper bearing solutions to enter the lode at that place. Miles away, in a different environment, the same lode is no more likely than some other one to become the solution channel.

2. Thomas S. Woods [18] attempted to show that the copper deposits of the region lay in certain master lodes where they were intersected by fissures of a north-northeasterly direction which led back into the footwall of the formations to intersect porphyry intrusives. Mr. Woods' proposal was to explore all intersections of the master lodes with these or other fissures of the same system which could be traced back to porphyries. Unfortunately for the plan, the data upon which it was founded were faulty. The fissure which he used to connect the Calumet conglomerate deposit with porphyry was known to play out long before it reached the porphyry and in depth along the conglomerate it split up and became inconspicuous. One of his "porphyries," the one chosen as the source of the Quincy ore body, was merely one of the common basic extrusives mapped as "porphyrite" not "porphyry." Since the two richest deposits of the district do not conform to the plan, it has no appeal.

[18] Woods, Thomas S., The porphyry intrusions of the Michigan copper district. Eng. and Min. Jour. 107: 299–302, 1919.

3. Attempts have been made to correlate ore bodies with local folding but there seems to be no such relationship. The Kearsarge and Baltic ore bodies are on anticlines as also are the scattered ore shoots on the Evergreen series near Rockland. The Isle Royale is on a syncline, and the two richest deposits, the Calumet conglomerate and the Quincy, are on an exceptionally straight unfolded stretch along their strike, although the dip of the Quincy formations flattens from 54° at the surface to 36° at the bottom of the mine.

4. There has been some speculation as to possible relationship between the ore bodies and the Greenstone flow. It has been pointed out that no ore bodies of importance occur above the Greenstone where it is thick, and that there are ore bodies above the horizon of the Greenstone where the flow itself is thin. The point seems to be strained however, inasmuch as in the section where the Greenstone is really thick there are no deposits of the first or second magnitude either above or below.

The major fissure deposits, which are relatively unimportant in production as compared with the conglomerate and amygdaloid ore bodies, do underlie the Greenstone where it is thickest (Fig. 10). In this respect they bear a resemblance to the native silver veins of Cobalt, Ontario, inasmuch as in both places the mineralized veins occur below sheet-like bodies of igneous rock where the latter have been folded.

5. As a result of a special study for the Copper Range Company, Paul Billingsley came to the conclusion that "there exists a comprehensive structure pattern throughout Keweenaw Point, which has determined the distribution of the copper deposits." What these significant structures are is expressed as follows: "Sixty per cent of the copper has come from the lodes clustered around the Ahmeek anticline, where the arched sector is combined with the north-south cross fold, with Keweenaw strands like the Mayflower fault, with the Kearsarge and Allouez slide faults, with tension fissures, and with a felsite intrusion which broke down westward into the favorable Calumet conglomerate. It seems clear, however, that stratigraphic factors have not in general been important. Where folds, thrust wedges, shearing slide faults and felsites are present, some one or another of the piled up amygdaloidal flows and sediments will be pervious enough to permit spreading out of mineral solutions. Conversely where structures are absent the most pervious fragmental crusts and conglomerate remain fresh and unmineralized." The essence of this statement seems to be that in areas where structures are present which provide deep seated channels, copper depositing solutions can find their way upward, forming ore bodies. That Billingsley recognizes that such structures are sufficiently prevalent to affect large areas favorably is indicated by his list of sections deserving exploration. It is not sufficiently restrictive to help much in eliminating blocks of ground which would be unfavorable. The present writers again point out that the Calumet conglomerate ore body is remarkably free from disturbances of the sort listed above and down to the depths exposed by mining operations it lies in a similarly undisturbed environment.

6. The Calumet and Hecla Special Survey emphasized the existence of different kinds of amygdaloids and recognized that all of the amygdaloid ore

bodies were predominantly in lode of the fragmental type. It was further found that there were through-going parts of the section in which the amygdaloids were dominantly fragmental, and between them were belts which were dominantly cellular. Since the known deposits were in fragmental lodes, what could be a more reasonable plan of exploration than to crosscut or drill through the belts where fragmented lodes were most abundant? Numerous explorations were laid out based upon this reasoning. It was not too sound as a guide for exploration however, since two amygdaloid deposits of the first order, the Quincy and the Kearsarge, are in fragmental lodes which lie in belts of dominantly cellular lodes. Thus explorations of the belts of fragmental lodes would fail to discover such important deposits as these two. This belt idea has been given little weight in planning explorations for many years.

7. In the hanging wall of all of the known deposits there is scattered copper mineralization of various types. This is called "hanging wall leakage" by us because we believe that it has been deposited by solutions which leaked out from the main channels especially along cross fractures. The copper was deposited in the fissures themselves and in amygdaloids and conglomerates near the fissure intersections. This type of copper occurrence is treated more fully elsewhere.[19] Some of the various leakages from the known deposits are as follows:

In the hanging wall of the Calumet conglomerate, nearby amygdaloids carry copper. This is especially true where the conglomerate itself thins down and becomes sandy. Just off the south margin of the ore body, stoping produced several hundred thousand pounds of copper in the overlying amygdaloid. A fissure which crossed the conglomerate had some apparently isolated copper masses on it many hundreds of feet in the hanging wall of the conglomerate.

In the hanging wall of the amygdaloids of the Quincy mine, a fissure, other wise known as the Hancock fault, is mineralized, as are some of the adjacent hanging wall amygdaloids near its intersection.

Crosscuts and drill holes in the hanging wall of the Kearsarge lode frequently encounter stray copper mineralization.

Some of the minor deposits which have yielded millions of pounds of copper may be leakages on a larger scale. As an example may be cited the old mine on the Allouez conglomerate at Allouez. This lies in the hanging wall of the Kearsarge amygdaloid ore shoot and it may be that its copper came from solutions which escaped from the Kearsarge lode along a cross fissure.

Other examples of leakage deposits in the hanging walls of known lodes could be cited, but these are sufficient to make clear one of the principles used in exploration. If known deposits have a halo of leakage or satellite deposits in their hanging walls, it is reasonable to explore toward the footwall of clusters of minor copper occurrences where no major feeding lode has yet been found. The most elaborate explorations based upon this principle were those which sought to find a parent lode related to the old Cliff and Phoenix fissure deposits. Such exploration was abandoned during the depression in

[19] Broderick, T. M., op. cit.

the early thirties, without being completed. There was some slight encouragement indicated in the exploration that there was a feeding lode for these fissure deposits, and the validity of the principle upon which the work was based is still to be proved or disproved.

8. A study of mineral zoning in the productive part of the district between Painesdale and Seneca indicates two "hot spots" or areas of highest temperature mineralization. One is at the Superior mine in the southern part of the area and the other is at the Seneca mine at the north end of the Kearsarge ore body. Clustered around on three sides of the southern "hot spot" are the Baltic lode mines, the Isle Royale, the Atlantic and the Quincy mines, which show progressively lower temperature mineralization with greater distance from the "hot spot" or epicentrum. Close by on the fourth side the formation is cut off by the Keweenaw fault (Fig. 6).

Southwestward from the Seneca "hot spot" are the southerly ore shoots on the Kearsarge lode, the Osceola ore body and the Calumet conglomerate ore body. These three deposits account for over 65 per cent of the district production. No lode deposits have been found symmetrically placed to the northeast, although the occurrence of the Cliff and Phoenix fissures gives proof that solutions were available in that general region. If copper deposits were symmetrically grouped around the southern "hot spot" why should they not be similarly grouped around the northern one? This argument was developed especially by W. H. Emmons in a study of the mineral zoning data which had been assembled by Calumet and Hecla geologists. It lends additional attractiveness to the search for the parent lodes of the fissures northeast of Seneca mentioned in earlier paragraphs.

Conjectures may be made as to what might be expected according to this concept between the northernmost deposit of the southern cluster and the southernmost deposit of the northern cluster. Great effort has been made to develop a profitable mine on the waning mineralization in that area on the extensions of the Kearsarge, Pewabic and Isle Royale lodes, without success. Long crosscuts in LaSalle and Franklin Jr. ground likewise explored large parts of the section. Perhaps the best that can be said is that this intervening ground has the tail ends of the northern cluster, such as the Kearsarge mineralization in LaSalle, and of the southern cluster, such as the Isle Royale lode in New Arcadian and the Pewabic lode in Franklin Jr.

9. There has long been an attempt to discover some linear pattern either along a straight line or series of straight lines, or along a curved line. If such a pattern could be discovered, other deposits might be sought where similar patterns are indicated, or along the extensions or gaps in the same pattern. An early expression of this idea of a linear pattern was made by L. C. Graton in the final Report on Exploration of the Special Geological Survey, dated April 24, 1924. After mentioning the generality which is often stated, that no two ore shoots occur in the same cross section in the district, and that notwithstanding some apparent exceptions to this rule, there is a tendency against bunching of the ore shoots into a short block or section of the series, he said, "If the deep-lying source of the copper solutions be assumed to have an elongated extension somewhat comparable to the extension of the produc-

tive region at the surface, and if that source be assumed to have emitted to the overlying rocks more or less equal quantities of copper in solution from mile to mile along its extent, then it might be expected that as these solutions moved in the main up the dip, though diverted and concentrated somewhat to follow the paths of easiest permeability, they would have arrived at the position of the present surface and be represented now as ore shoots with a distribution more or less evenly scattered along the axis of elongation of the source." This is an excellent statement, revealing the hopes which can be aroused by a concept of a linear pattern of deposits. Condensed, it suggests that the known deposits are a linear expression of a deep-lying linear source, which if it emitted solutions essentially uniformly should have similarly evenly distributed deposits along its axis of elongation.

This idea of continuity of solution emission from an elongated source yielding a corresponding continuity of copper deposits is of course fascinating to the explorer. The simplest result of such a mechanism would be one long deposit in a single conglomerate or amygdaloid lying directly up dip from the linear source which it tapped. We know that even though there may be such a linear source the pattern of the deposits is far more complicated. In discussing this subject only the major deposits in the heart of the district from Painesdale to Mohawk will be considered. These deposits lie in seven different horizons nearly 10,000 feet apart stratigraphically. Perhaps instead of there being one linear source, there are more than one.

As recognized in Graton's statement quoted above, the solutions did not rise directly up the dip but were deflected by barriers of various sorts. The pattern of greatest significance is not the pattern at the present surface modified as it is by the internal permeability structures of the lodes, but the pattern as close to the source as possible. In the 22 years since Graton's statement was made, considerably more has been learned concerning the trend of the ore shoots in depth. Accordingly a map has been prepared showing the pattern at surface and that at the greatest depths to which the mines have been developed (Fig. 6).

It will be noted that the Quincy, Calumet conglomerate, Osceola and Kearsarge ore bodies lie along a fairly straight line which transgresses from lower to higher horizons from north to south. The question as to what happens to any linear expression of the pattern from Quincy south can be answered in two ways. If one chooses to connect the remaining two major deposits to the south, namely those on the Isle Royale and Baltic lodes, the line must be bent or curved to include them. On the other hand the Atlantic ore body lies closely on the extension of the straight line developed by the Kearsarge, Osceola, Calumet and Quincy deposits. An objection that the Atlantic ore body is not a major deposit and can be ignored in setting up the pattern may not be valid. The Atlantic ore body was not worked out to its limits, but only to the boundaries determined by property ownership. It was low grade and when the mine caved as a result of insufficient support, it was abandoned and never reopened. There is a possibility that had it been worked to its lateral limits and to greater depth it would have yielded a production nearly as great as that of the Isle Royale lode. If in recognition of this importance

of the Atlantic ore body, the straight line coming from the north down to the Quincy is projected to pass through the Atlantic, the Isle Royale and Baltic lodes then might lie along another, perhaps nearly a parallel line.

The structure which is responsible for a linear pattern, if there is anything of the sort, is in depth far beyond the range of observation. It might be a fault whose outcrop is under the lake, or otherwise concealed, it might be the line of intersection of the Keweenaw fault or a branch of it with bedding planes, or it might be the roof of a large intrusive. Some of the conjectures which have arisen from an attempt to recognize some linear pattern which could be applied to exploration will be discussed.

10. There has been a persistent feeling that the Keweenaw fault, which cuts off the Keweenawan copper bearing formation on its southeastern or footwall side, and the shattered zone in the hanging wall of the fault, has been the deep seated channel for copper bearing solutions, which at certain places where conditions were favorable escaped into the lodes following and mineralizing them in their further course upward. Observations of the dip of the fault indicate that it may be flatter than the beds, so that in depth stratigraphically higher and higher formations would be intersected. This structural relation of fault to bedding would make the idea of the latter tapping the deep seated fault solution channel seem plausible.

All of the major deposits lie within 8,000 feet of the fault (or if the Atlantic is included as a major deposit, within 10,000 feet of the fault), as measured stratigraphically. This stratigraphic interval of 8,000 feet in the hanging wall of the Keweenaw fault has been called the Belt of Major Lodes, and since by far the greater number of mines and larger part of the production has come from the upper 2,000 feet of the belt, from 6,000 to 8,000 feet stratigraphically above the fault, this part of the belt was called the Mineralization Crest. Since the fault is not exactly parallel to the beds but gradually swings back and forth, cutting across them both in strike and dip, the Mineralization Crest likewise swings across the beds. Further out from the fault, for about 8,000 feet more, occur the less important deposits of this part of the district, most of which are of the leakage type. This upper 8,000 feet was called the Belt of Major Leakages.

Fig. 7 shows diagrammatically the relationships of fault, bedding, the Belt of Major Lodes with the Mineralization Crest at its top and the Belt of Major Leakages between the sections at Painesdale and Mandan. It is apparent that because the fault cuts back into the footwall on the northern, or right side of the diagram, the Belt of Major Lodes likewise cuts back into the footwall. The beds which were favorably located within the Belt of Major Lodes, in the southern or left part of the area, are well above it in the northern or to the right in the diagram. It was perfectly natural that the part of the section containing the horizons in which most of the major ore bodies occurred further south should have received most of the exploration in its extension northward. Furthermore, the presence of the rich fissure ore bodies in this same part of the section in the northern part of the district was evidence that copper depositing solutions had travelled through those formations.

However, the Belt of Major Lodes to the north lay well in the footwall of

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those horizons which were more favored to the south, and it had been relatively neglected. Therefore it was thought wise to explore it and accordingly considerable diamond drilling was done in the zone. The results have been discouraging to date, and lead to the conclusions that if there is any linear arrangement of the ore bodies, such as suggested by the Mineralization Crest concept, either there is some other control than stratigraphic distance from the fault, determining its position, or the solutions were too scanty in this northerly area to form a lode deposit, or if they do exist the present erosion surface is still too high to reveal them.

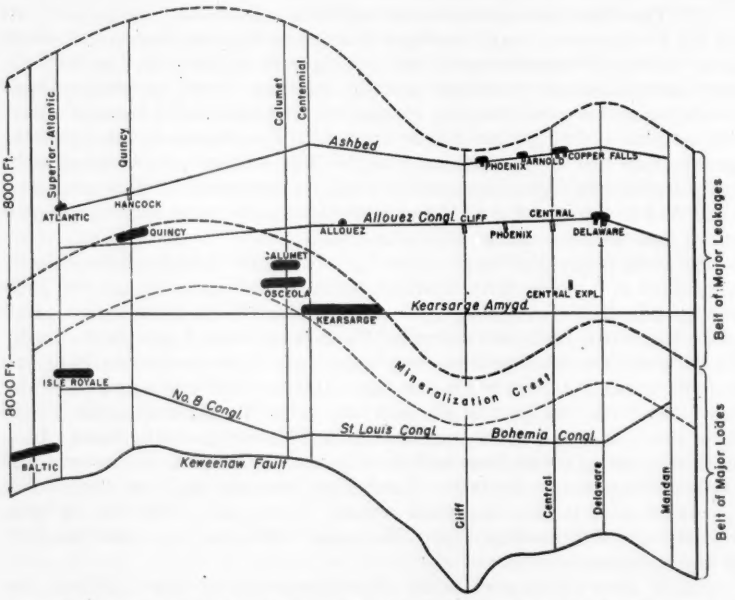

FIG. 7. Sections showing stratigraphic distance of ore bodies from Keweenaw fault.

11. The next attempt to define a pattern for the major ore bodies involved a consideration of the distribution of associated gangue and ore minerals. There are fissures containing arsenides of copper, nickel and cobalt, and copper sulphides (mostly chalcocite), associated with the end members of the group of major deposits, namely those on the Baltic and Isle Royale lodes at the south, and those at the northern end of the Kearsarge ore body at the north. In places these minerals are also found in the lodes near the fissures. The deposits in the middle of the group do not have these minerals either in the lodes or associated fissures. This distribution of associated arsenides and sulphides has been expressed in its relationship to the Keweenaw fault. The

deposits nearest the fault have these minerals and those further away do not. If the fault is regarded as the deep seated channel and the idea that the elimination of arsenic and sulphur is accomplished by contact with the oxidizing environment of the lodes is accepted, then the lodes higher in the series having tapped the fault at a greater depth would have a higher degree of elimination because of longer contact of the solutions with the oxidizing environment and vice versa (Fig. 8).

By drawing an arc connecting all the major deposits (ignoring the Atlantic) one gets what was called the Mineralization Axis. Drawing a line for the upper limits of the arsenide-sulphide occurrences one gets a similar line which is the reciprocal of the Mineralization Axis in that as the latter advances into the hanging wall, away from the fault, the former recedes toward the fault. If the line connecting the major lode deposits, or the Mineralization Axis is an arc penetrating the areas of chalcocite-arsenide occurrences at each end, why not draw similar arcs between other chalcocite-arsenide areas beyond the region of the known lodes, and explore along these arcs? Starting

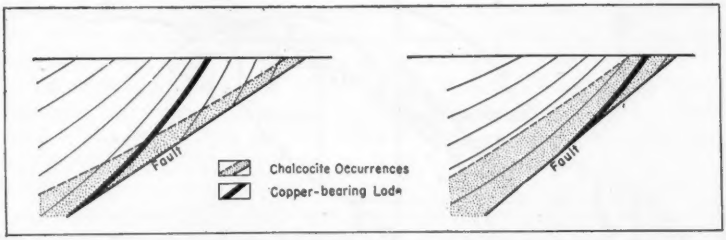

FIG. 8. Sections showing possible relations of Keweenaw fault, chalcocite occurrences and copper bearing lodes.

with the sulphide-arsenide region of the north end of the Kearsarge lode, it may be extended by scattered occurrences approaching the fault at Gratiot Lake. Another area of chalcocite occurrences is found at Mt. Bohemia, further north (Fig. 9). One may draw a hypothetical extension of the Mineralization Axis swinging it into the hanging wall where the chalcocite-arsenide line swings toward the footwall and vice versa.

In the enthusiasm which this concept inspired, it was expanded to include minerals other than the metallic sulphides and arsenides. The distribution and abundance of the latter were dependent primarily upon the degree of oxidation of the mineralizing solutions. The zoning of minerals within the individual lodes was thought to be due to a temperature control rather than a chemical control such as oxidation and it was further proposed that the ore depositing solutions, coursing through the lodes, might have heated up the adjacent rock for thousands of feet on either side. If so, this would give an opportunity for a zoning of gangue minerals not only within the lodes themselves but in the hanging and footwall rocks, the higher temperature minerals being deposited nearest the lode deposits and progressively lower tempera-

ture minerals at progressively greater distances from them. Furthermore, if the major deposits lay along an axis of mineralization which was a curved line, swinging back and forth across the formation, this line would have a temperature significance, being the up dip expression of solution source. Since this line then would represent a belt of higher temperatures, the gangue minerals should be distributed in zones related to it.

It so happened that the data on minerals present in critical unexplored areas were scanty enough so that there was great latitude in where the mineral zones were drawn, and having set up a curved Mineralization Axis, based upon fragmentary data on chalcocite occurrences, a still more imaginary set of curves were drawn for the gangue minerals, bearing what was thought to be the proper theoretical relationship to the Mineralization Axis.

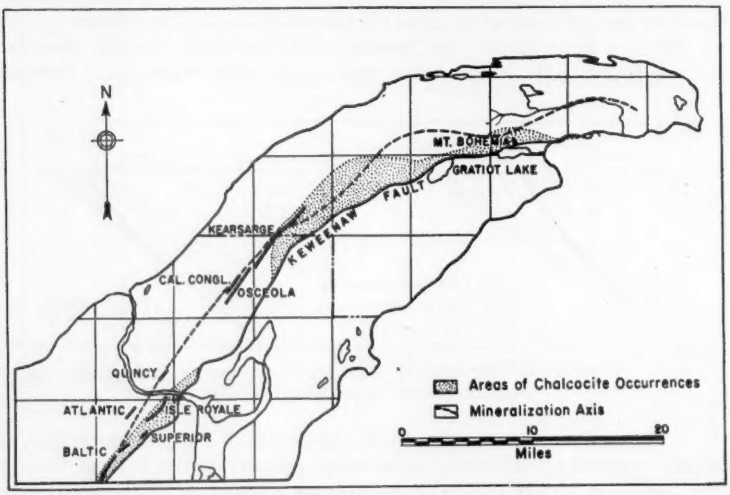

FIG. 9. Map showing relationship of major ore bodies and areas of chalcocite occurrences.

In all of this conjecture there were certain disturbing facts which had to be set aside as being out of line. For example, the great abundance of a relatively cool mineral, red feldspar, in the West lode, only 50 feet in the hanging wall of the Baltic lode, both in the Copper Range mines and the Superior, indicated a very rapid falling off of the high temperature of the main lode, toward the West lode.

As drilling filled in some of the gaps in information, the mineral zoning curves were of necessity radically changed, and while we are open minded about the possibility of there being a broad zoning of the gangue minerals related to the heating effects of the ore depositing solutions, our present tendency is to regard these effects as being pretty closely confined to the lodes themselves. This is consistent with the evidence of the main Baltic and Baltic

West lodes as cited above. Even though there was leakage of solutions out into the West lode in sufficient quantity to deposit a fair amount of copper, nevertheless there is a considerable difference in temperature indicated by the cooler minerals present in the hanging lode.

That there may be a regional zoning related in some way to the copper deposits should be borne in mind, and perhaps its pattern can be worked out. If so, it might be of great assistance in exploring. For the present, the picture is by no means clear, and the accumulation of a vast amount of quantitative mineralogical data and their study will be required to bring any order out of the present uncertainties.

12. Some mention should be made of the possible connection of faulting and ore bodies. In summarizing the work of several summer field seasons, the Michigan Geological Survey stated that "In general it may be said that the use of the dip needle for following the flows and mapping the structure in the Copper Country has been successful. The faulted areas are shown up by this method and the undisturbed flows become evident in the study of this work. The location of a large number of longitudinal faults has also been a feature of this work, and from a study of these faults as related to present and past mining operations it is quite evident that the faulting had an important place in the localization of the copper deposits." [20]

Naturally among the first researches of the Calumet and Hecla Special Geological Survey was the relation of faults, fissures and ore bodies. Almost the first property studied was the White Pine mine, where the ore body is pretty definitely related to faulting. In the later studies of the Isle Royale and and Baltic lodes it seemed likely that solutions were introduced into the footwall side of the lodes by many tight near strike fissures dipping steeper than the lodes. But to establish a relationship of these or any other of the lode deposits of the main part of the district to definite longitudinal faults, as is said to be "quite evident" by the State Survey, was found to be impossible, unless one is satisfied in simply believing that because there are examples of such faults cutting ore bodies, a genetic relationship is thereby established.

Two classic examples frequently cited in this connection are the Quincy or Hancock fault and the Isle Royale fault. The former actually diverges from the Quincy ore body in depth and the spatial relationships of the Quincy ore shoot and the fault are such that there can seem to be no connection in depth. In fact, rather than the fault having fed the lode at depth the reverse seems to be the situation.[21]

In the case of the Isle Royale fault, the mine openings reveal that the grade of the ore body is not much different below the fault intersection where the feeding relationship would not be possible, from that above the intersection where it might be thought to operate. We do regard the Isle Royale fault as just one of a group of scores or hundreds of the steep, near-strike fissures, each of which may have fed its share of solution into that lode.

[20] Pardee, Franklin G., Recent work of the state geological surveys in Huronian and Keweenawan areas. Lake Superior Mining Inst., Proc. 27: 171, 1929.

[21] Broderick, T. M., op. cit., p. 849.

Other attempts on our part and that of others to discover a relationship between specific faults and lode mineralization were made in the Kearsarge and Baltic amygdaloid and the Calumet conglomerate ore bodies. These likewise were unsuccessful. We do keep in mind however the possibility that the Keweenaw fault may have been the major solution channel which either itself or through its branches introduced the copper solutions into the lodes at great depth. But this relationship, if it exists, is far below the zone of observation, in the realm of conjecture.

13. It is of interest to observe that the region of the commercial and near commercial cross fissure deposits just below the Greenstone, including the Cliff, Phoenix, Central and Delaware group is beneath the downwarped portion of the base of that flow as shown in Fig. 10. Even the most attractive of a still lower order of fissure deposits, judged by their copper contents, such as the Robbins, St. Clair, Central Exploration, Madison and others, lie in the same region. Similarly, the best mineralization in the Ashbed, just below No. 17 conglomerate, and in its associated cross fissures, the Owl Creek, Petherick and others, lies in this same cross section of maximum Greenstone thickening at the Copper Falls mine. There is a similar relationship between the silver bearing veins of Cobalt, Ontario, and fracturing and folding in diabase sills about 1,000 feet in thickness.

Pursuing the matter further, it has been pointed out that in Michigan the ore shoots on the Kearsarge and Osceola amygdaloids occur where the flows of which they are the tops are thickest. Finally if the stratigraphic column of the productive area is plotted with No. 17 conglomerate as a base it will be seen that the underlying beds have sagged relatively to accommodate a thicker stratigraphic column (Fig. 10). The major ore bodies all lie within this depressed area, on the southwest flank and toward its center. Thus the distribution of the major ore bodies bears a relationship to a major thickening of the section similar to that which the fissure and Ashbed amygdaloid deposits of Keweenaw County bear to the thickening of the Greenstone. Whether there is any genetic significance to this relationship or whether it is merely coincidence awaits further study.

Summary.—Some of the attempts which have been made to relate the ore bodies to geologic structures or to arrange them in some pattern with respect to each other or to zones of associated minerals have been described. Others, such as a relationship to the configuration of the Keweenaw Fault, are not touched upon at present either because they have already been discussed elsewhere or because they are too vague to be treated. Some of the above discussions of the various theories are condensations of much more voluminous treatment in reports to the company. Some of these ideas never had any standing with us, and others have been developed, tried out and discarded, nevertheless for the sake of completeness, they have been discussed. Such discussions will point out to other students the dead ends that they lead to, or perhaps suggest lines of investigation that have been overlooked in the past. The remainder of the ideas discussed above are still in good standing as aids in exploration.

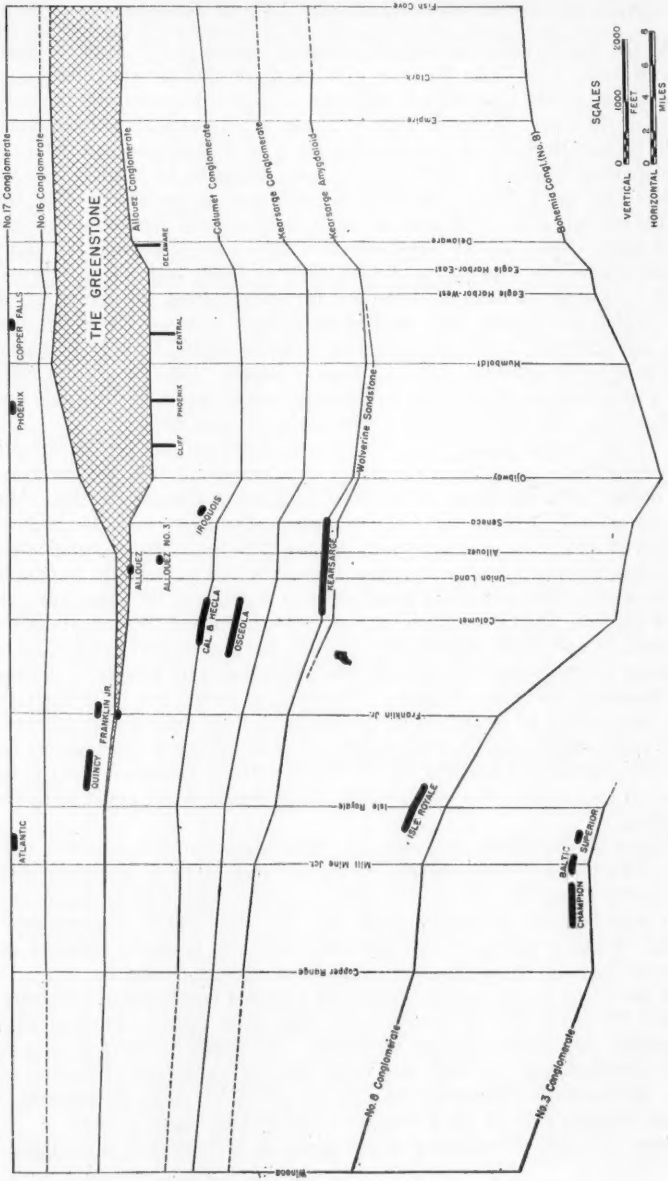

FIG. 10. Sections showing variations in stratigraphic column and the positions of ore bodies.

CONGLOMERATES AS SOLUTION CHANNELS.

As has been brought out above, geological studies of the copper formation on both limbs of the Lake Superior syncline agree that the most likely source of the lavas and the interbedded sediments is down the present dip toward the center of the lake. If this is true, it would be expected that the sediments would become thicker and coarser with depth as they approached the source. Developments in the district have given two examples for study. The most familiar one, the Calumet conglomerate, will now be described. The other one, the recently discovered area on the Houghton conglomerate, will be mentioned later. The Calumet conglomerate is known for many miles in Houghton and Keweenaw Counties as a thin, shaly or sandy bed. Two salients of coarse conglomeratic material extended far enough from the source, so that after folding and erosion they reached the present rock surface as two horns 2,500 and 3,500 feet in length, projecting from the thicker main body which at the bottom of the mine was 2½ to 3 miles in length. Had the erosion surface been a thousand feet higher, the outcropping conglomerate horns would probably have been shorter and thinner than at the present surface.

Such an inverted funnel shape for salients of diminishing pebble deposition and accumulation would be expected to occur commonly near the margins of such bodies, with the source of material lying down the present dip. Many horizons characterized by thin conglomerate, sandstone or shale are known in the district and if we are right in assuming that the Calumet conglomerate offers just one example of a prevalent type of behavior, it would be expected that these other thin sediments would develop in depth in the same way. We cannot say how deep it would be necessary to go to find the salients of conglomerate in any given sedimentary horizon, but the present erosion surface cuts many conglomerates at such a position that they vary greatly in thickness and character from place to place. Therefore, it would not be unlikely that many thin sediments would be found locally to have outcrops of salients of coarse conglomerate, perhaps not 3,500 feet in length, as in the Calumet conglomerate, but several hundred feet in length. If the salients did not extend to present rock surface they might occur within depths which could be reached by drilling.

Having developed the idea that the exceedingly favorable inverted funnel shape of the Calumet conglomerate is a feature likely to occur elsewhere, either outcropping along the course of sediments prevailingly thin or to be found within such horizons at drilling depth, the next argument to be considered is whether or not it might be expected that while the favorable Calumet conglomerate may not be unique, the ore body occupying it may be.

So far in the history of the district the Calumet conglomerate ore body is unique. Its production and profits have been about equal to those of all the amygdaloid and fissure deposits combined. Furthermore, there is only one known conglomerate ore body and there are five amygdaloid horizons with major ore bodies, not including the Atlantic or Ashbed lode, the recently discovered Iroquois lode, or the Evergreen series of Ontonagon County.

There is a line of reasoning which gives an even greater importance to

the role of conglomerates in connection with the ore bodies of the district. In order to receive and conduct ore depositing solutions ascending from depths, the "lode" itself must be permeable to great depths or connect with some other permeable channel extending to great depths. Thus the copper in the Calumet conglomerate and the Quincy amygdaloid ore bodies is known to extend down the dip for about 10,000 feet with no sign of stopping. Conglomerates, because they thicken and coarsen toward their source, should persist forming permeable channels for miles down the dip. Just what the situation with the fragmental amygdaloids may be is not fully known, but the indications in the mines of the Baltic and Kearsarge lodes are that they become thinner, tighter and less fragmental in depth. This opinion is shared by the operators on these lodes. Studies in other lava fields likewise indicate that this decrease in fragmental character of the tops toward the source is a common feature of lava flows. Thus we have conglomerates becoming more permeable and amygdaloids less permeable in depth. Therefore we can assume that just as the conglomerate salients tend to close upward, forming the inverted funnels favorable to solution flow concentration (with attendant richer ore), so the amygdaloid channels open upward, tending to disperse the solutions. (If this is true there should be some indication of "roots" in the amygdaloid deposits. The Baltic and Kearsarge amygdaloid deposits have suggestions of such "roots.")

If there is such a pinching out of amygdaloids at comparatively shallow depths, what brought the solutions from the deep sources to the bottoms of the amygdaloid channels? In the case of the Baltic and Isle Royale lodes a set of steep fissures swinging into the lodes from the footwall may have served as feeders but even though such fissures did serve to introduce solutions into the amygdaloids, it does not follow that they were other than secondary channels, connecting the superficial amygdaloid channel with a more persistent lode channel lying in the footwall and extending to greater depths.

An examination of the various amygdaloids suggests what such deeper footwall channels might be. Fig. 10 illustrates some of the points to be discussed.

The Kearsarge amygdaloid (accounting for about 18 per cent of the district production) is the first amygdaloid in the hanging wall of the Wolverine sandstone. Both the Kearsarge amygdaloid and the Wolverine sandstone are known for many miles along the strike and over most of its known length, the former is barren of copper and the latter is thin and shaly. However, in the same section where the Kearsarge amygdaloid becomes mineralized, the underlying Wolverine sandstone, about 200 feet in the footwall, thickens up considerably. In other words, the Kearsarge amygdaloid is the first amygdaloid above a sediment and that sediment attains its maximum known development where the copper mineralization occurs in the overlying lode. The Kearsarge lode becomes thinner and tighter in depth in the same area and it may be that the Wolverine sandstone becomes more permeable in depth. The copper solutions may have ascended along the Wolverine sandstone, jumping across to the Kearsarge amygdaloid where the Wolverine tightened at higher elevations. This transfer, if it did take place, would have been below the pres-

ent mine operations and from time to time holes are being drilled from the bottom Kearsarge openings to test the sandstone for any change in character with depth. So far no significant change in the sandstone has developed.

The Baltic amygdaloid (accounting for about 12 per cent of the district production) is the first amygdaloid above No. 3 conglomerate. This amygdaloid, like the Kearsarge, becomes less permeable in depth. It is not known just what the changes in No. 3 conglomerate may be in depth, but it is known to be thin and sandy near surface in the footwall of the mineralized parts of the Baltic lode and the possibility that the Baltic lode solutions ascended along No. 3 conglomerate in depth before jumping across to the Baltic lode in its hanging wall, should be considered. Since this discussion was originally written some years ago, developments in the Champion mine indicate that the copper in the Baltic lode is approaching exhaustion but that there are interesting quantities of copper at the horizon of the conglomerate and the underlying amygdaloid on which it was deposited.[22] This gives some substantiation to the idea that the conglomerate is the deep solution channel for the Baltic lode mineralization.

Thus about 50 per cent of the district production came from a sediment (the Calumet conglomerate) and an additional 30 per cent came from two amygdaloids which are the first amygdaloids above sediments. If we admit the possibility that these latter sediments may be the channels in depth, 80 per cent of the district production would be definitely related to sediments.

The other amygdaloid deposits do not bear quite such a close spatial relationship to conglomerates although there are sediments not too far away which may have been the channels in depth. Thus the Pewabic series of amygdaloids worked in the Quincy mine (about 11 per cent of the district production) is not far in the hanging wall of No. 15 conglomerate. The latter has had scattering mineralization from Quincy to Franklin Jr. where some mining of low grade material was done on it. The Isle Royale amygdaloid (about 3 per cent of the district production) is the first permeable amygdaloid in the hanging wall of No. 8 conglomerate. The Osceola amygdaloid (about 6 per cent of the district production) might be remotely connected with the Kearsarge conglomerate as it seems to be the first consistently permeable amygdaloid above that horizon. Some of the minor deposits likewise may be related to sediments. Thus the Atlantic or Ashbed lode is between and not far from conglomerates 16 and 17. The Central fissure ore body bottomed at the Kearsarge conglomerate, where the latter began to open out downward.[23] The Minesota fissure and branches lay on and in the hanging of the Minesota conglomerate.

If these relationships between the positions of the amygdaloid ore bodies and underlying sediments are not merely matters of chance, but are to be interpreted in the way herein suggested, it means that these sediments were the channels in depth. This does not necessarily mean that a conglomerate ore body will be found in depth, in the footwall of every amygdaloid ore body. On the contrary there is evidence in this district, as in others, that where

[22] Annual Report, Copper Range Company, 1944.
[23] Broderick, T. M., op. cit., p. 854.

solutions pass from one environment into another there is not necessarily continuity of ore deposition. In some cases the ore may not deposit until the second environment is reached and in other cases there is a large spatial gap between the ore in the first environment and that in the second. Examples of the latter in this district are the ore shoots on the Hancock fault, thousands of feet from the probable place where the solutions took off from the Quincy or Pewabic amygdaloid ore shoot,[24] and a similar deposition of stray masses of copper thousands of feet in the hanging wall on a fissure intersecting the Calumet conglomerate.

The recent discovery of an ore shoot on the Houghton conglomerate in Allouez ground may give further light on this matter of the importance of conglomerates as channels. Like the Calumet conglomerate, the Houghton is known for many miles as a thin bed of felsitic sand and grit. At Allouez, a lens of felsitic conglomerate about 1,000 feet in length at rock surface is found, and this lengthens and thickens with depth. It has attractive copper values in places and is now being explored underground. In general there is a resemblance to the Calumet conglomerate conditions which obtained where the ore body was formed. However, there are reasons to suspect that the Houghton conglomerate itself was not a major solution channel, but that solutions leaking out from the Kearsarge amygdaloid ore shoot in the footwall, mineralized the conglomerate to a relatively mild degree. The importance of this deposit commercially and whether it is a leakage will not be known until additional openings are made in depth.

The occurrence of felsite flows along horizons of felsite conglomerate in the Lake Superior Keweenawan series has suggested that at least some of the conglomerates have resulted from the breakdown of those flows at the same horizons. If this is true it would be expected that each conglomerate horizon in depth should have a felsite flow along it. There is a suggestion in the account of Schwartz and Sandberg [25] that the horizons of acidic flows in the Minnesota Keweenawan were especially favored by intrusives although Schwartz states that there is too much irregularity to justify formulating a definite rule for this tendency.[26] Insofar as it is true it can be fitted into an intriguing and plausible hypothesis for the course of the ore bearing solutions (Fig. 11). An underlying intrusive sends apophyses up into the tilted Keweenawan series. Especially favored as horizons for such intrusives would be the felsite flows, which further up dip, away from their source, become the conglomerate beds. These in turn become thinner, sandier and finer grained and hence less permeable. The course of ascending copper bearing solutions would be as follows. They emanated from the apices of the underlying intrusive which perhaps are the apophyses intruded into the horizons of felsitic flows. They followed up the brittle shattered acidic flows, into the derived conglomerates. Where these became impermeable they jumped across into the nearest permeable amygdaloid, which in some cases was the first amygda-

[24] Broderick, T. M., op. cit., p. 849.

[25] Schwartz, George M., and Sandberg, Adolph E., Rock series in diabase sills at Duluth, Minnesota. Bull. Geol. Soc. Am. 51: 1135–1172, 1940.

[26] Personal communication.

loid above the conglomerate. Where conditions were favorable the copper was deposited along this path, over a great vertical range, forming the conglomerate and amygdaloid ore bodies of the district. In some places in the Lake Superior Keweenawan the relationships of source, zone of deposition and present erosion surface may have been such that the copper deposits have now been removed and in other places the erosion may not yet be deep enough to uncover them. In Fig. 11, erosion surfaces corresponding to those for the Baltic or Isle Royale amygdaloids and the Calumet conglomerate ore bodies are shown. Diamond drilling in the Rockland area, Ontonagon County,

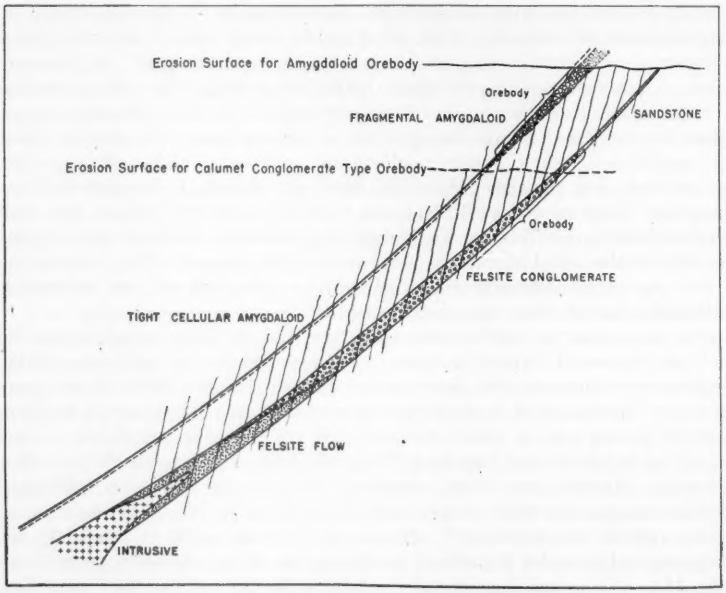

FIG. 11. Hypothetical section showing course of ascending solutions and relations of amygdaloid and conglomerate ore bodies.

penetrated certain felsitic conglomerates which were considerably epidotized, but carried no copper. Epidotization of felsitic sediments commonly accompanies copper deposition. Perhaps the unmineralized epidotic sediments of the Rockland area were the channels of copper bearing solutions which did not deposit copper until they reached higher elevations now eroded.

ORIGIN OF DEPOSITS.

Summary of Preferred Theory.—In arriving at an explanation of the origin of the native copper deposits the geologists of the Calumet and Hecla Special Investigation started with an attempt to reduce a seemingly complicated

situation to its essentials. The ore mineral being an unusual one, the probability was that a similarly unusual set of conditions was responsible for the deposits and that these conditions must be adequate to explain the deposits of all types in the district, namely those in conglomerates, amygdaloids and fissures.

It was stated that "if the features common to all types can be separated from the numerous features that are not common to all, the causes of copper precipitation and the nature of the mineralizing solutions are more likely to appear." [27] These common features are as follows:

(1) The deposits are in permeable rocks.

(2) The amygdaloids and conglomerates are high in ferric iron and the deposits are in these rocks themselves or in cross fissures which have frequent intersections with such rocks.

(3) The minerals common to all types are few; other than the primary minerals of the host rocks themselves, they are quartz, calcite, epidote, pumpellyite, and a potash mineral, either a red feldspar or sericite.

The zeolites and associated silicates such as prehnite and datolite, which have been connected with the deposits in the geological literature and which have even defined the type as the "Zeolitic Native Copper Deposits," are entirely lacking in the felsitic material of the copper bearing conglomerates.

(4) The deposition of copper is associated with a reduction of ferric iron.

The conclusion was reached that the mineralization was accomplished during a single period of somewhat complex activities that followed the completion of all the essential deformation which the rocks reveal.

The difficulties of the theories which attempt to explain the deposition by descending waters or by diffusion are very serious.[28]

The explanation which best fits the facts and requirments is that heated copper-bearing solutions emanated from an underlying intrusive, ascended permeable channels, and deposited their copper when and where conditions for precipitation were right. One, if not the only, factor which caused the native metal to precipitate rather than minerals of the sulphide group which are the common copper-bearing minerals elsewhere, was the fact that the lodes were high in ferric iron. Chemical research had demonstrated that the type of solutions which would normally deposit sulphides, could react with the hematite of the lodes so as to oxidize the sulphur in the solutions and result in the deposition of the metal.

Next to the Michigan copper district in importance as a producer of native copper is the Coro Coro District in Bolivia. There the copper occurs in red sandstone. The latter is bleached around the copper and there are no lavas known anywhere nearby. Chalcocite, domeykite, native silver and gypsum occur as in Michigan. The theory proposed for the deposits of Michigan applies equally well to those of Coro Coro, where all of the essential conditions are present and where none of the bewildering unessential complications such as basalts and zeolites occur. The fact that the theory is the only one so far

[27] Butler, B. S., and Burbank, W. S., op. cit., p. 119.
[28] Butler, B. S., and Burbank, W. S., op. cit., p. 124.

proposed which accounts for the genesis of both of the two most important native copper deposits of the world gives it strong additional support. Singewald discussed the genesis of the deposits of the two districts in a very interesting and able manner, having visited both of them.[29]

Criticisms of Theory.—A. C. Lane and Waldemar Lindgren do not agree with the explanation of the genesis of the Michigan deposits which was summarized above. After its publication in Professional Paper 144, each of them stated objections to it. These objections will be presented and discussed. Additional points bearing on the genesis also will be brought out.

All basalts carry primary copper, as do other igneous rocks. Various estimates give about .01 per cent as an average for igneous rocks in general and .015 per cent up to .03 per cent and even more for basic lavas. In the study of differentiation of the Michigan Keweenawan lavas, an average primary copper content of .01 per cent was arrived at.[30] Thus the lavas here have a primary copper content which is in the lower range of the averages for basalts the world over. However, this copper is not uniformly distributed throughout an individual flow. It was concentrated in certain definite parts of the flows by differentiation processes. In the Greenstone, where differentiation had proceeded further than in the thinner flows, it was especially concentrated in the pegmatitic or doleritic layers of the upper half. These have over twice the average copper content of the entire flow. The Kearsarge flow likewise shows that copper was subject to the processes of differentiation within the flow. In discussing this fact it was mentioned that these processes which concentrated the primary copper within the flows themselves would have had a much greater opportunity to operate in a magma chamber. There was no feeling that these processes operating within the individual flows could account for the deposits of commercial copper. It was simply pointed out that they gave a suggestion as to the concentration by differentiation within a deep magma chamber, resulting in the solutions which escaped and deposited their copper at a later time, in conglomerates and cross fissures as well as in the amygdaloidal tops of traps. The idea was expressed as follows, "When differentiation by gaseous transfer in these relatively thin, quickly chilled surface flows can increase the concentration of certain elements like copper, one hundred per cent and more in certain horizons, it is not difficult to picture the possibilities in the great magma chambers of large intrusives."[31] Dr. Lane, in discussing this work, suggests that this concentration of primary copper by differentiation within the individual flows is in some direct way responsible for the commercial deposits which we regard as being of later age and entirely different in origin. He suggests that by differentiation in the flows the copper may by volatile transfer "be concentrated here and there in concentratable quantity."[32] The thought here seems to be that later solutions,

[29] Singewald, Joseph T., Jr., Genetic comparison of Michigan and Bolivian copper deposits. ECON. GEOL. 23: 55–61, 1928.

[30] Broderick, T. M., and Hohl, C. D., Differentiation in traps and ore deposition. ECON. GEOL. 30: 303, 1935.

[31] Broderick, T. M., and Hohl, C. D., op. cit., p. 311.

[32] Lane, A. C., discussion "Differentiation in traps and ore deposition." ECON. GEOL. 30: 927, 1935.

which Lane's previous work would indicate he thought would be descending, would still further concentrate these primary concentrations, to form the commercial deposits. This additional suggestion does not avoid the difficulties in the theory of descending waters as the agents of copper deposition already referred to.

Lindgren in the latest edition of "Mineral Deposits" discussed the various views of the origin of the deposits including especially the one of the Calumet and Hecla Special Survey as published in Professional Paper 144. Lindgren still felt that the copper was leached from the traps in whole or in part, the agent of leaching and redeposition being in large part meteoric water. The following quotations are taken from his discussion.

As to source of the copper he says that basic igneous rocks commonly contain from .02 to .04 per cent copper. (The paper on Differentiation in which the average copper content of the Michigan traps was said to be .01 per cent had not appeared until after Lindgren's book was published.) He then states that "The suggestion that the whole or a part of the copper in the deposits was extracted by waters from the rock itself almost forces itself upon the observer, and although a number of investigators uphold the idea of ascending deep-seated waters of magmatic origin as a carrier of the copper, the suggestion noted above cannot as yet be discarded." He then says, "They (the authors of Professional Paper 144) assume—which is not quite so evident—that the waters were of magmatic origin and reducing character, and that they contained copper and sulphur, likewise of magmatic origin." As a further difficulty he cites, "the enormous amount of magmatic water required. It will no doubt be necessary to assume a very liberal mixture of meteoric water. Basaltic magmas are not rich in water." Finally he says, "If strongly active hot waters ascended the lodes, it is not reasonable to assume that they could traverse distances of 20,000 to 40,000 feet in basaltic rocks containing from 0.01 to 0.03 per cent of copper without dissolving (and depositing) a large amount of this metal. The concentration to produce ore would be only 100 times the original content of the rock." [33]

Brief comments on these quotations are as follows. Whatever the type of water which is responsible for the transportation and deposition of the copper, and whatever the source of the solutions and of their contents, in addition to the copper and sulphur mentioned by Lindgren, they contained arsenic, antimony, silver, gold, nickel and cobalt. As to the enormous amount of water required to deposit the copper of the district, it should be pointed out that many other districts likewise required an enormous amount of water for their metal deposition. Butte, for example, has produced about the same amount of copper as Michigan and in addition about a billion dollars worth of gold, silver, zinc and lead. The theory of origin under discussion did not intend to assume that the solutions came from basaltic magma. The Duluth gabbro of probable late Keweenawan age has abundant acidic "Red Rock" associated with it and both Keweenawan and Killarnean granites are common

[33] Lindgren, Waldemar, Mineral Deposits. McGraw-Hill Book Co., pp. 514–525, 1933.

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in the Lake Superior Region. They are in places associated with important mineralization as in the Sudbury Basin.

So far there has been no evidence seen of the leaching of the primary copper of the flows. All of the visible evidence indicates that for most of the lodes the solution channels to great depths were restricted to the amygdaloids and conglomerates in which the deposits are found. The primary copper content of the amygdaloids themselves is difficult to obtain, because of the difficulty in distinguishing between the primary copper and the later copper disseminated in small quantities all over the district, during the period of ore deposition. However, it can be assumed that the quickly chilled flow tops most likely carried the average copper of the flows as a whole, namely 0.01 per cent. The felsite conglomerates probably had a primary copper content of about the same as the felsites, namely 0.003 per cent. If the solution channels in depth had the same cross section as they did where commercial copper was deposited, it means that in order to get an accumulation of copper to form only the mined out part of the Quincy mine, the solutions would have had to pick up all of the copper through the channel of ascent for about 200 miles down the dip. This ignores the copper in the eroded upper part of the ore body, and that in its unknown extension in depth below the bottom of the mine where it is still rich. Even assuming that the solution channel increased in its length along the strike with greater depth, so that the volume of leached amygdaloid per unit of depth was much greater than the volume in which the copper was precipitated, it is still difficult to bring the calculation into terms which are rational.

If the same calculation is applied to the Calumet conglomerate ore body, the results are even more out of line with probabilities. The ore body averaged over 2½ per cent, and the felsite conglomerate, probably .003 per cent in primary copper content. Assuming a uniform channel cross section, and for purposes of calculation the admittedly erroneous assumptions that there has been no ore eroded, nor any extension of the copper deposit below the mine bottom, the ascending solutions would have had to pick up all of the copper in the conglomerate for 800 miles down the dip. However, it is known that the cross section of the conglomerate does increase rapidly down the dip and if one is willing to assume a vigorous solution flow throughout a great volume of conglomerate in depth, it is only a matter of selecting the proper rate of increase in dimensions to get the 800 to 1 concentration required.

Such calculations of course are not of serious import to the writers and they are only included here to show that the 100 to 1 concentration mentioned by Lindgren as necessary to raise the primary copper content of the traps to that of the commercial deposits would not be a simple thing to attain. In any event a much higher concentration ratio would be necessary in the case of the Calumet conglomerate ore body.

Sandell and Goldich show that the two flows which were studied in detail for their differentiation characteristics have the following average metal contents.[34]

[34] Sandell, Ernest B., and Goldich, Samuel S., The rarer metallic constituents of some American igneous rocks. Jour. Geol. 51: 103, 1943.

	The Kearsarge.	The Greenstone.
Copper	0.0094	0.0121
Zinc	0.0114	0.0095
Lead	0.0008	>0.0005
Nickel	0.017	0.0179
Cobalt	0.0038	0.0045

If as suggested by Lindgren, the leaching of such material resulted in the concentration of the 10 billion pounds of copper mined, what happened to the other metals, especially zinc and nickel which occur in about the same amount in the traps as the primary copper, or to cobalt, the content of which is over one-third that of the primary copper. Expanding the quotation from Lindgren cited above, to take into account these other metals, it would read "If strongly active hot waters ascended the lodes, it is not reasonable to assume that they could traverse distances of 20,000 to 40,000 feet in basaltic rocks containing from 0.01 to 0.03 per cent copper (or zinc or nickel and over one-third as much cobalt) without dissolving and depositing a large amount of this metal (these metals). The concentration to produce ore would be only 100 times the original content of the rock." No concentrations of zinc are known in the Lake Superior Keweenawan. Locally in some of the copper arsenide fissures there are small amounts of nickel and cobalt arsenides, but these are only mineralogical curiosities. Therefore in order to explain the copper deposits as being due to a leaching and concentration of the primary copper of the traps, it is necessary to assume a selective action which did not operate to form zinc, nickel or cobalt deposits in a similar fashion.

It must not be inferred from the above discussion that the writers have been or are blind to any facts because they happen to be difficult to fit into the preferred theory of genesis. It is simply that no other theory has been proposed which fits so many of the facts and what appear to be the essential conditions. Perhaps the outstanding difficulty in the theory is that the heavy, and in some cases the richest, and in other cases practically the only copper in an amygdaloid occurs along its lower or footwall side where it changes or merges into the footwall trap. Various explanations have been proposed to fit this occurrence reasonably into the theory, but these are not entirely satisfactory. It was proposed that an earlier wave of solutions deposited gangue minerals in the upper more fragmental and hence more permeable part of the lode and that when the later copper deposition took place the originally less permeable lower part at and just above the contact was then more permeable than the plugged up hanging wall side of the lode. This is not reasonable unless there was intervening movement resulting in the shattering of the lower contact between trap and amygdaloid. Some evidence of there being such a shattered condition in this zone is seen in the Isle Royale lode, in which the concentration of copper on the foot side to its exclusion on the hanging side is most marked. Another idea is that there was a sheeted zone there produced by early cooling stresses and that while the upper fragmental part of the lode is locally the most permeable, it occurs in disconnected patches, isolated from each other by impermeable cellular lode, and the sheeted footwall zone had the through-going permeability.

Discussion of Syngenetic Origin.—The evidence obtained in the flow differentiation studies that the primary copper content is higher just under the amygdaloid than the average for the flow as a whole, raises a question as to whether certain flows had an extraordinarily high copper content, and that the differentiation during the cooling of the flow might not have been carried to such an extreme that it produced the commercial concentrations of copper in the amygdaloids. This theory might gain additional support in that the best amygdaloid copper tends to be on the footwall side of the lode, where it might be imagined that the volatiles, ascending throughout the lower part of the flow, become trapped under the amygdaloidal crust already formed. This differs from the theories already discussed in that it would make the deposits syngenetic. Still other attractiveness might be given to the idea by the fact that several of the important amygdaloid deposits are at the tops of thick flows; even further, they are in places where the flow attains its greatest thickness. The Kearsarge is the ideal example of the kind.

The fact that the amygdaloid ore bodies are in the main in amygdaloids of the fragmental type also may be considered to lend support to the idea. Insofar as the breaking up or fragmentation of the lode was accomplished by the explosive evolution of volatiles from the flow, it might be thought that this means that those flows had an excessive volatile content in general or at least in those parts where fragmentation occurred. If copper in some chemical combination was one of the volatiles then where volatiles were most abundant, copper would likewise be most abundant. Since both fragmentation of amygdaloids and primary copper content are therefore related to abundance of volatiles an obvious inference is that copper concentrations should occur in fragmental amygdaloids, which is the actual case.

This idea of syngenetic origin is only attractive if many of the essential requirements of a satisfactory explanation are ignored. Some of these will be listed below.

In the first place the Calumet conglomerate ore body is the preeminent deposit in the district, both as to grade and total copper content. As mined it averaged over 2½ per cent copper as compared with the less than 1 per cent for the amygdaloids, and it produced practically as much copper as all of the other deposits, amygdaloids and fissures, combined. The syngenetic theory in its simplest terms cannot explain this deposit, and it is difficult for the writers to conceive of any modification that will explain it. Neither will it explain the deposits in the sandstone of the White Pine area. The only alternative to discarding this theory is to abandon the principle that has guided the Calumet and Hecla geologists in setting up a theory of genesis, namely that it must explain all of the deposits of the district, and to take the position that the deposits in amygdaloids have a different origin from those in the interbedded sediments. It would seem that such a position should be taken only as a last resort.

Since commercial deposits of native copper are so rare, any theory which would account for both the Michigan copper and that of the next most important copper district, Coro Coro, would thereby gain measurably in prestige. Conversely any theory which would not apply to both districts is to be dis-

trusted. The Coro Coro deposits are accepted as being epigenetic and therefore the syngenetic theory for genesis of the Michigan amygdaloid deposits fails to explain the Coro Coro deposits.

Another guiding principle in selecting a theory to explain the deposits is that the structural features of the district had all been well developed at the time of copper deposition. The beds were tilted and sets of cross fractures related to the tilting had been formed. The solutions deposited copper in seams, joints and fractures of all degrees of extent and importance. Where the copper solutions mineralized an amygdaloid, they also penetrated the cooling joints at the base of the immediately overlying flow, depositing copper in them. It is found filling the pencil like pipe amygdules of the base of the overlying flow, forming the solid copper "spikes" so admired by mineral collectors. Fissures which cross the amygdaloids and extend into the hanging wall have copper masses and sheets along them which likewise extend into the hanging wall. These features show that the hanging wall trap was in place and that deformation had occured when copper was deposited.

Even more leakage copper is found along stronger cross fissures thousands of feet in the hanging wall of amygdaloid deposits which they intersect. This can only mean that the thousands of feet of section had accumulated and had been deformed when the solutions did their work. The Central, which was one of the most important of the cross fissure deposits, had copper mineralization on it rather continuously across its intersection with 2,640 feet of amygdaloids, traps and sediments.

A satisfactory theory must be adaptable to the fact that the deposits are decidedly localized. Keweenawan traps and amygdaloids encircle Lake Superior. While the sections are not known in any detail outside of the copper district, except only locally, the meagre descriptions indicate that amygdaloids of the fragmental type occur all around the lake, not only on Keweenaw Peninsula but in Wisconsin, Minnesota, Isle Royal Island and Point Mamainse. If copper deposits are syngenetic, why do they not likewise encircle the Lake? Why should the lavas poured out in all directions from a source somewhere near the middle of the present lake, only have copper in quantity in the flows or the parts of flows which reached the Michigan copper district? Why should such primary concentration occur in this restricted area of the Keweenawan time after time throughout the accumulation of a lava column miles in thickness? The deposits which together have furnished over 95 per cent of the district production are even restricted to 26 miles along the strike of the southern limb of the syncline.

Furthermore, within the productive part of the district itself, there are dozens of barren fragmental amygdaloids, indistinguishable from those which contained copper. If fragmentation is an evidence of an abundance of volatiles, why was there an abundance of copper in some of the flows with fragmental tops and not in others?

Even more difficult to explain by the syngenetic theory is the fact that some fragmental lodes are copper bearing only in certain local areas and are barren elsewhere. A good example of this is the Osceola amygdaloid. For many miles it is a thick and fragmental lode. Toward the south it is practically

barren of copper, but suddenly, just south of Calumet, copper came in. The lode-bearing copper is in every respect of the same character as that not bearing copper. Between the mineralized and unmineralized lode there is a bar of tight cellular amygdaloid only one or two hundreds of feet in length along the strike. This pitches at a low angle to the south extending for thousands of feet in depth along the lode. In the fragmental lode below this bar, the copper starts in. Above it the same kind of lode is barren. According to the epigenetic theory, ascending solutions were deflected by the barrier and the copper deposited underneath it. The solutions did not penetrate it, hence there is no copper above it. How can this occurrence be explained by the syngenetic theory?

The zoning of gangue minerals, rock alteration and copper-arsenic ratio within individual lodes fits readily into the epigenetic theory, but it is difficult to explain by the syngenetic theory.

The Kearsage amygdaloid with its complex of lode copper, arsenide bearing cross fissures, mass copper fissures and zoning of arsenic and gangue minerals can be explained consistently by the epigenetic theory. To separate the individual components of this complex, making a part of it, the amygdaloid mineralization, of syngenetic origin and another part of it, the cross fissure mineralization, epigenetic, seems to be going out of the way to call upon coincidence. Why should later hydrothermal solutions ascending along cross fissures pick out from all of the lodes which they crossed an intersection with the same lode for their mineral deposition which earlier syngenetic processes had favored? Incidentally the primary copper content of the Kearsarge flow is about the same as that of other flows which have no ore bodies. In fact no flow has been found with a primary copper content far out of line with the average.

In the above argument for and against syngenetic origin it was assumed that the flows having fragmental amygdaloids were especially abundant in volatiles including copper compounds. Another point of view might be that inasmuch as all of the flows seem to have had about the same primary copper percentage, to regard those which are thickest as being the ones most likely to have copper deposits. Not only would the total copper content of the thicker flows be greater, but also there would be the opportunity for more complete differentiation. Evidence of the more complete differentiation is afforded by the formation of the coarse pegmatitic layers which occur in the upper parts of such flows as the Greenstone and the big trap above No. 8 conglomerate, 1,600 and 1,000 feet thick respectively. Neither of these flows has any known native copper deposit. The Greenstone does have a concentration of copper in the doleritic layers, bringing it up from the flow average of .012 per cent to .023 to .029 per cent in the two such layers assayed. Sulphur likewise shows an increase in these layers.

At or just below the amygdaloidal top of the Greenstone there are occasional local concentrations of sulphide. Geologists of the present U. S. Geological Survey party recently discovered such an occurrence. Two layers a few inches thick, separated by four feet of barren trap, carried considerable chalcocite intergrown with specularite. Samples across the two mineralized

layers and the trap between assayed .268 per cent copper, .006 oz. gold and .82 oz. silver per ton. This occurrence is of interest because it seems to be syngenetic and if so represents the maximum known concentration of copper by what can be reasonably regarded as differentiation within a flow. If thickness of flow and degree of differentiation are the factors essential in forming this type of deposit, there is probably no other place in the district more favorable than the top of the Greenstone. In the eight or nine sections exposing this zone in the Greenstone, no other such occurrence has been found although in one section there is a small concentration of pyrite noted at the top of the flow.

In summary, the argument for a syngenetic origin not only is built upon an underestimation of the importance of certain conditions under which the copper occurs, but also upon an exaggeration of the adequacy of any known syngenetic process which has been operative in the lavas. This discussion has not been presented in order to set up a dummy to be knocked down. On the contrary we and others feel that even at this advanced stage in the study of these deposits, a thorough review of the entire theoretical basis of our geological picture should be made from time to time, and the recent work on differentiation in the individual flows has served to bring this matter of syngenetic origin into the foreground for reconsideration.

EXPLORATION FOR NEW DEPOSITS.

For a large part of the period since the final report of the Special Survey in 1924, explorations have been conducted in the district. These have been of various kinds and have been based upon various geological ideas. Diamond drilling has been carried on fairly continuously. The primary purpose of the drilling has of course been the discovery of copper, but it also serves another end. In all mining districts one of the first objectives of geological study is to prepare a surface geological map. This has been difficult for the Michigan copper district because of the prevailing drift cover and diamond drilling goes a long ways in providing the information necessary to build up such a map.

As a method of copper discovery, diamond drilling has decided drawbacks. The erratic distribution of copper in the amygdaloid deposits makes it rather unlikely that holes widely spaced, over one quarter of a mile apart and more in the reconnaissance drilling, will reveal it. Only by closer spacing of holes can an area be safely eliminated as not copper bearing by drilling alone. Even in the search for conglomerate deposits, where the copper is much more uniformly distributed, the fact that the Calumet conglomerate ore body and the one now being explored on the Houghton conglomerate came to rock surface as short projecting lenses of a larger body opening out downward, makes it a possibility that other unknown conglomerate deposits, if they exist, may be likewise limited in extent near surface. Correspondingly closely spaced drilling would be necessary to discover such bodies. It is employed so commonly in the district only because there is as yet no better substitute for it in the preliminary stages of exploration.

In spite of its drawbacks, drilling has in recent years discovered four ore bodies, one of each kind that exists in the district. These four deposits are as follows:

1. Drilling outlined an area of mineralization in a small fissure deposit of the general character of the larger ones of the Cliff and Central type. After exploring and mining in it to a depth of over 450 feet, it was abandoned, as the tendency of the ore shoot was to become smaller in depth. This exploration produced over 2,600,000 pounds of copper.

2. Drilling on the Seneca and Ojibway properties acquired by the Company in recent years, discovered attractive mineralization in an amygdaloid which was named the Iroquois lode. Detailed exploration outlined two shoots of better drill hole intersections and one of these is being examined by underground openings. The values so far have been spotty.

3. Drilling in the vicinity of Ahmeek village discovered a thick lens of conglomerate in the horizon known as the Houghton conglomerate. Like the Calumet conglomerate it is known for many miles as a horizon of felsitic sandstone, in many places with a very thin layer of felsitic pebbles at the top. In the area of the new discovery it widened out as did the Calumet conglomerate and like it, showed attractive mineralization in that place. Detailed drilling outlined the copper bearing shoot and underground openings are now exploring it.[35]

4. In a report by the Special Survey to the Company in 1921, it was pointed out that earlier diamond drilling had located a favorable structure, namely a branch of the White Pine fault, with an increase in copper near it, to the east of the White Pine mine in Ontonagon County. It was stated that more drilling to the southward along this branch fault might show it to be of increasing importance nearer the main fault and might encounter more ore in the sandstone under the Nonesuch shale, of the type already known in the White Pine mine and elsewhere in that part of the district. Maps showing this structure were turned over to the Geological Survey for publication, as was also the report which discussed the possibility that there might be important mineralization associated with it. The structure referred to is the fault "S" of the text and is shown on Plate 33 designated as "Fault indicated by offset in contours."[36] The Copper Range Company later purchased the property and in recent years has explored it by diamond drilling. The annual report of that company for the year 1937 states that exploration to the south of the mine (in

[35] For the sake of accuracy in the record, it should be stated that both the Iroquois amygdaloid and the Houghton conglomerate had attracted favorable attention in an exploratory crosscut from No. 2 Allouez Shaft some years previous to the drilling referred to. There the Iroquois amygdaloid was opened for 1,100 feet along the strike and then abandoned as being too erratic and low grade. The ore shoots on the same lode outlined by diamond drilling in more recent years are several miles away and drilling can be fairly credited with a discovery. In the case of the Houghton conglomerate, it occurred in the same Allouez crosscut as a thin sandstone about a foot thick but it carried a little copper, and this exposure simply emphasized it as a horizon to be watched in future explorations to see what the degree of mineralization might be if it ever opened out into a real conglomerate lens. Here again, it is felt that drilling can fairly be credited with the discovery of the mineralized shoot now being explored.

[36] Butler, B. S., and Burbank, W. S., op. cit., pp. 172–174 and Plate 33.

the region mentioned in Professional Paper 144) had disclosed interesting mineralization. A shaft is now being sunk to obtain further information on the occurrence.

These four discoveries serve to increase confidence in diamond drilling as a method of exploration in the district. Its reliability, however, is in proportion to the closeness with which holes can be spaced. This in turn is dependent upon the cost. Any discoveries, modifications or changes in procedure which will increase core recovery or lower the cost will make the drilling more effective and will make possible the drilling of more holes.

Increasing core recovery is a matter of research in mechanical equipment and operation. Bortz bits, double tube core barrels and the recent improvements in the latter have resulted in better core recovery. Anything which minimizes opposing interests of drill contractor and client will also be effective.

Any substantial lowering in costs would justify a corresponding increase in drilling. There are very few areas in the district from south of Victoria to the end of the point which are thoroughly explored.

The maximum utilization of the footage drilled is a responsibility of the geologist. Where cross sectioning is the objective, inclined holes at right angles to the bedding are chosen. Where depth of intersection is important, vertical holes are drilled. In areas where it is thought that there are possibilities for both amygdaloid or conglomerate ore and in addition ore shoots on the fissures which are nearly vertical and at right angles to the strike of the beds, inclined holes are drilled which are not at right angles to the strike of the beds, but rake across it at an angle calculated to give maximum coverage of both beds and the fissure system.

Of even greater importance is the working out of geological principles which will indicate areas where more intensive exploration is warranted or where the explorations already made are sufficient or where no exploration is justified. Some progress has been made in these directions, but much more must be accomplished if substantial savings are to be made in giving the district the exploration it deserves. At present the data of chief importance which are being accumulated to attain these ends are those giving the distribution of minor copper showings. The known deposits have halos of minor copper occurrences in the beds and cross fissures, for hundreds of feet in their hanging walls. Mapping of minor occurrences already known and new ones encountered in drilling in areas where a known major lode cannot account for them is being kept up with the hope that it will lead to the parent lodes.

If some pattern, linear or otherwise, could be found which truly has a significance in depicting structural relationships, it would be of great help in exploring. The various attempts at this have been outlined above, and it is a matter of continuous study. The realization that the Atlantic ore body is possibly of the same order of magnitude as the Isle Royale and should therefore receive correspondingly greater emphasis in considering patterns of ore distribution may modify some of the theories which assume patterns of the simple linear type.

So far no line of reasoning, geological or other, has been suggested which, had all of the known deposits of the district been discovered with the exception of the Calumet conglomerate, would have led to the discovery of the latter. (Assuming of course that the conglomeratic glacial debris were so dispersed and buried that it did not give the clue.) As a matter of fact one of the very rules which even yet is regarded with respect would have operated to cause a lack of interest in the region where the conglomerate ore body comes to rock surface. That is the generality that no two major deposits are likely to occur in the same cross section. Since the Osceola ore body and southern marginal deposits of the Kearsarge lode occur in the same cross section as the Calumet conglomerate ore shoot, the immediate vicinity would have attracted at best only perfunctory interest.

Various electrical and magnetic geophysical methods have been tried out in attempts to find some electrical effects directly related or magnetic effects indirectly related to the copper mineralization. Among the electrical methods tried were self potential, induction, resistivity and radio frequency. There was no reason to believe that copper lodes gave any response, at least none that could be distinguished from those of varying rock conductivity, ground waters or overburden differences. Magnetic observations were made and it was found that many of the trap beds could be traced along the strike by dip needle observations. These trials were described in 1928.[37] Since then other geophysical investigations have been made, especially by the Michigan College of Mining and Technology, including work with the Gish Rooney resistivity methods, and some with radio frequency. There has been no reason to change our former attitude.

Dip needle work showed that one of the cross fissures of Keweenaw County could be traced by sufficiently detailed work. For 50 to over 100 feet on both sides, the normal magnetism of the formations crossed was decidedly diminished. While it is our opinion that this anomalous magnetic behavior adjacent to the fissure bears no relationship to the copper mineralization within the fissure at that point, we cannot yet be sure that such is the case.

Electrical as well as magnetic methods serve to delineate various bed rock characteristics and structures, such as the strike of beds, the location of fissures, the boundaries between diverse types such as sandstones and traps, and intrusives or extrusive acidic rocks and traps. The need for such information is not very great however. The State Geological Survey has spent some summer seasons taking dip needle readings, but so far as we can discern these observations have not been susceptible to any interpretation which would be directly applicable to copper discovery.

The district still stands as a challenge to the geophysicists however. With one of the best of electrical conductors as an ore mineral, the hope that some electrical method will be devised which can detect deposits of it is ever with us.

In conclusion, the question confronting a mining company with large and favorably located land holdings in this district is whether the chances of new

[37] Broderick, T. M., and Hohl, C. D., Geophysical methods applied to exploration and geologic mapping in the Michigan copper district. ECON. GEOL. 23: 489–514, 1928.

ore discovery are great enough to justify exploration. This must be considered from two points of view. In the first place do the conditions make it likely or even possible that there are undiscovered deposits in the district. The second point of view is whether their chance of discovery appeals to an individual company. This is in turn dependent upon the company policy, its holdings, investment in the district and other factors whose consideration is of a nature outside the scope of this paper. However, the consideration of whether or not there may be undiscovered ore bodies in this district should be touched upon.

Mining geologists, both in the employ of mining companies and in governmental organizations, are stating with increasing frequency as time goes on, their belief that the best chance for ore discovery in the United States is within and along the margins and extensions of the known districts. These districts of course have been the objects of attention by explorers for many years, and any undiscovered deposits can exist only because they have been effectively concealed. It is proper, therefore, in considering chances for discovery in any given district, to deliberately look for any reasonable condition or combination of conditions which can occur in that district to make such a possibility of concealment a rational one. Had they not been so concealed they would have already been found.

It is not too easy to reason that there must be undiscovered deposits in any district. However, in the case of the Michigan copper district it is easy to show that various conditions are present which would conceal such deposits if they did exist. In the first place the known deposits were discovered because they outcropped, or as in the case of the Calumet conglomerate, because attention was called to the locality by the presence of conspicuous glacial boulders of ore. The percentage of bed rock exposed is very small and even this is likely to be the more resistant barren trap and the optimist might reason that if this small percentage outcropping exposed the several deposits which it did, how many more must there be concealed in the much larger areas where outcrops are lacking.

The objection that such deposits under the drift cover if they existed would be revealed by the presence of copper in the drift may not be as serious as might seem at first glance. The conditions under which glacial copper has been found are not too well known and it would be a fitting subject for study. The prehistoric miners, who dug hundreds of pits and trenches in the district and on Isle Royal Island, may be assumed to have developed keen eyes for copper. Evidence of their mining activities extends from end to end of the district, well out into Keweenaw County to the north, and south of Victoria at the other end of the district. It would seem a fair assumption that they would have been the first to find any fields of exceptionally abundant glacial copper lying about on the surface of the ground, just as they were the first to find all of the outcropping deposits. The white men coming along later had the advantage of the existence of the prehistoric diggings in pointing out the deposits in ledge, but they also had the disadvantage of having only a picked over terrain so far as glacial copper is concerned.

At any rate, the records of glacial copper discoveries by the white men indicate that some sort of excavation accounts for most of them. The farmers plowing or spading for gardens probably have found the greatest amount. Digging for basements, foundations, pipe lines and road and railroad cuts have contributed their share. There is some reason to believe that the copper boulders increase in weight and abundance with depth in the overburden, but this is not yet well established. At least, it seems to be a reasonable deduction that when the activities of the white men started, the discovery of abundant glacial copper required the coincidence of breaking through the surface of the ground, in most cases by farming, in an area where such deposits existed. The outstanding areas of glacial copper discovery were in the farming country in the hanging wall of the Calumet conglomerate, Osceola and Pewabic amygdaloid deposits. There are vast tracts of land which might have glacial copper where farming or other activities have not disturbed the top soil.

The fact that there were at least two directions of glacial movement, one from the hanging toward the footwall and the other from the foot to the hanging wall of the formations, means that corresponding complexities have resulted in drift distribution. What appears to be glacial debris from the Osceola amygdaloid and the Calumet conglomerate has been found in abundance in the footwall as well as in the hanging wall of the outcrops of those lodes. Variations in the directions and relative intensities of glacial action might well give different distribution of drift material in different areas and there is not enough information to determine which conditions existed in various parts of the district. A light scouring action of the earlier hanging to foot movement might result in little movement of the residual copper resting on the pre-glacial surface, especially if it had shifted around and accumulated in pre-glacial depressions. If the later foot to hanging movement accomplished vigorous scouring, the copper boulders would then be dispersed and fanned out on the hanging side alone. Or, the reverse conditions could be imagined, leaving the greater accumulation on the footwall side of the lodes. In the latter case, the boulder field might be concealed by the later drift with no copper in it.

If there were thorough scouring action during both glacial movements, the dispersion of material due to one succeeding the other might be so great that the tracing of copper boulder discoveries to any particular ore body would be impossible. As is well known, copper is found in glacial drift over an area of many thousands of square miles in a southerly direction from possible sources.

Therefore, the fact that there are no known areas with abundant glacial copper to point the way to an undiscovered parent lode is not a serious argument against the existence either of such fields of glacial copper or of undiscovered ore bodies.

Although it is reassuring to realize that there is nothing in our knowledge (or lack of knowledge) of drift copper to preclude the possibility of their being important copper deposits coming up to ledge surface, there are other considerations which still further render our appraisal of exploration possibilities independent of the occurrence of glacial copper. Furthermore, they tend to make the existing explorations of less importance in eliminating any great part of the district as having no possibility of undiscovered deposits. Ref-

erences have already been made to these considerations but they will bear repeating in this connection. One of these is the fact that the outcrop of the Calumet conglomerate ore body was relatively short and interrupted by barren stretches, and the probability that a higher erosion surface would have made it still shorter. Other conglomerate ore bodies might come to ledge with similarly short expressions and so could be easily missed in most of the drilling which has been done.

Another fact is that there is evidence that in amygdaloid deposits, the occurrence of areas or patches of impermeable lode forced the solutions at various elevations to flow through more restricted channels in the lode. If an amygdaloid ore body came to rock surface where such a condition existed its restricted length of mineralized outcrop would be correspondingly difficult to discover. Furthermore, the glaciers in such cases would only have had short outcrops from which to obtain copper debris.

The Michigan copper district therefore would seem to be one where there are ample reasons why unknown ore bodies could have remained undiscovered throughout the many years during which it has been explored. Furthermore, because of the erratic distribution of the copper in the lodes, and the fact that the only method of exploring such lodes in the initial stages, namely by diamond drilling, is admittedly inadequate in such a situation, the district will probably be classed as incompletely explored for many years. Whether or not it will survive the conditions which the immediate future has to offer, as a continuous producer, cannot be foretold. However, there are substantial reserves of lower grade ores in the district, and the time will undoubtedly come when such ores in the United States will be exploited.

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ARTIFICIAL RECHARGE OF PRODUCTIVE GROUND-WATER AQUIFERS IN NEW JERSEY.[1]

HENRY C. BARKSDALE AND GEORGE D. DEBUCHANANNE.

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ABSTRACT.

Artificial recharge by water spreading is practiced in several places in New Jersey. Rates of recharge ranging from 3,000 to 125,000 gallons per acre per day have been measured at the Perth Amboy Water Works, where artificial recharge of the Old Bridge sand, of upper Cretaceous age, has been practiced for more than 40 years. At the Duhernal development, which also draws from the Old Bridge sand, four or five million gallons daily is now derived from artificial recharge. This rate will probably increase with further lowering of the water table near the lake. For many years the Princeton Water Company has pumped water from a stream for recharging the Stockton sandstone, of Triassic age. The Lake Mohawk-Sparta Water Company spreads water underground by means of covered, gravel-filled ditches to recharge a shallow aquifer in its well field. The City of East Orange spreads the water from several small streams over parts of the intake area of the Quaternary beds supplying its wells. The estimated total recharge there is about two million gallons daily. Closely related to artificial recharge are those instances wherein well sites are chosen to take advantage of potential recharge from existing bodies of surface water. At the Borough of Manville no water spreading operations are conducted, but about three quarters of the water from its wells is derived by recharge from the Raritan River. The silting of water spreading areas may impair their effectiveness considerably. In some instances the growth of aquatic vegetation seems to reduce the ill effects of silting.

INTRODUCTION.

ARTIFICIAL recharge is becoming an increasingly important means of maintaining an assured yield from some important well fields in New Jersey.

[1] Published with the permission of the Director of the Geological Survey, United States Department of the Interior, and the Commissioner of Conservation, State of New Jersey, Department of Conservation.

Presented before the Society of Economic Geologists, Pittsburgh Meeting, Dec., 1945.

Several successful developments using various methods of water-spreading in the vicinity of the wells have been in operation for periods ranging from a few years to 30 or 40 years. The practice has, however, been limited mainly to well fields in which the water is encountered under water-table conditions or in which the pumping wells are relatively close to the intake area of the sand. The authors know of no successful large-scale recharge operations in this State in which water is introduced into an aquifer through wells. There follows a description of some of the more notable developments for artificial recharge in New Jersey.

PERTH AMBOY WATER WORKS.

Artificial recharge has been practiced at the Perth Amboy Water Works at Runyon for many years. Actually the Runyon Pond, which is the oldest of the water-spreading works at this plant antedates the construction of the wells that are now recharged from it. The first water delivered to the city from this plant was derived from the pond. The first wells (drilled in 1897) tapped the Farrington sand member of the Raritan formation which is of Upper Cretaceous age. Due to the presence of confining layers of clay, this aquifer contains water under artesian head. For several years the natural flow of these wells was enough to supply the city's needs. The first wells tapping the Old Bridge sand member of the Raritan formation were drilled in 1902.

The Old Bridge sand lies at or near the surface at the Perth Amboy Water Works and contains water under water-table conditions. In this vicinity it is generally covered by a thin veneer of permeable sand and gravel belonging to the Cape May formation of Quaternary age, but there is no confining layer. Water percolates freely through the materials of the Cape May and into the Old Bridge sand. The bottom of the Old Bridge sand is about 80 feet below the land surface.

A widespread system of wells has been constructed by the Perth Amboy Water Department to draw from this sand, which is now the principal source of water for the city. The location of the wells and of the various developments for artificial recharge are shown on Fig. 1. The pumping is all done at the main station and some of the suction mains are almost a mile in length. With a system of this nature it is obviously essential not to lower the ground-water level too much in order to avoid breaking suction.

Although the Runyon Pond (No. 1 on Fig. 1) was in existence when the first wells were drilled, its importance as a source of water for the wells drawing from the Old Bridge sand was soon recognized by those in charge of the water works. As the demands on the plant increased various measures were taken to increase the effectiveness of the recharge from the pond. A shallow part of the pond (No. 3 on Fig. 1) was dredged to a depth of about 2 feet to increase its effectiveness as a recharge area. At first, control works were installed to keep heavily silt-laden water out of this area, but they were abandoned in a few years. A large ditch or canal was dug along the line of wells extending south across the pond (No. 4 on Fig. 1) and a similar canal was dug along a line of wells that parallels Deep Run (No. 5 on Fig. 1).

During the first World War a group of basins (No. 2 on the map) were constructed north of the pond and water was pumped into them from Deep Run to recharge the sand around some of the more efficient wells near the plant. This was discontinued after the war because of decreased demand and the expense involved. Detailed records of this operation are no longer available, but the information at hand seems to indicate that recharge rates in the order of 750,000 gallons per acre per day were achieved.

In recent years the system of recharge canals was extended still further and new canals along pipelines extending south and east of the pond were constructed (Nos. 6, 7, 8 on Fig. 1). The efficiency of this recharge system

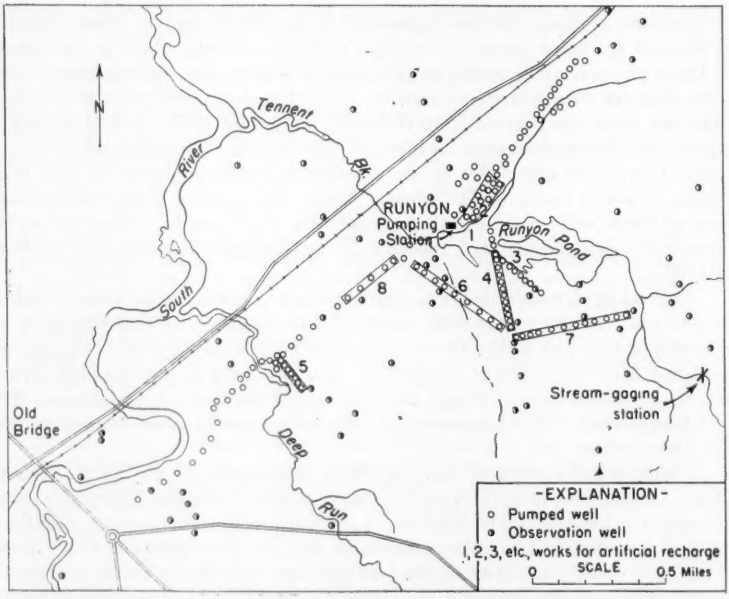

FIG. 1. Map showing locations of wells and of developments for artificial recharge at the Perth Amboy Water Works.

is such that most of the flow of Tennent Brook is now absorbed by the sands and relatively little water flows over the spillway at Runyon except at times of flood or when prolonged periods of rainfall have filled the ground-water reservoir to such an extent that little additional recharge can be absorbed.

Records of precipitation and evaporation from a land pan have been maintained at Runyon for many years. For several years a stream-gaging station was maintained on Tennent Brook above the pond at Runyon. Most of the data necessary for estimating the recharge from the pond have thus been available. It has been impossible to make continuous measurements of the

flow past the dam, but the water level in the pond is below the spillway for considerable periods in almost every summer. There have thus been numerous short periods when it was possible to estimate the combined rate of recharge from the pond and from the oldest of the canals connected with it. The stream-gaging station was abandoned before the construction of the last three canals. The rates of recharge determined for about 25 such periods varied from about 3,000 to about 125,000 gallons per acre per day. The lowest rates represented periods when the water in the pond was low and covered only a small area which had been almost completely sealed by a thick deposit of sludge from the washing of filters in the iron removal plant. It is believed that the higher rates are more truly representative of the normal rate of recharge from the pond.

DUHERNAL WATER SUPPLY.

The Duhernal water supply is a cooperative development furnishing water to factories of the duPont, Hercules and National Lead Companies in Sayreville. It is located near Old Bridge only a few miles southwest of the Perth Amboy water works, and is believed to be unique among the water supplies in New Jersey in that its original plans included the construction of a dam and lake adjacent to the well field for the purpose of supplying artificial recharge. All other artificial recharge developments known to the authors within the State have been constructed to supplement the yield in existing well fields.

The Duhernal Lake and the locations of wells around it are shown on Fig. 2. The Duhernal wells are located on the south side of the lake. The group of five wells shown on the north side belong to the Peter J. Schweitzer Company, and the single well just north of the dam belongs to the Anheuser-Busch Company. All these wells draw water from the Old Bridge sand in its intake area, and they all receive substantial recharge from the Duhernal Lake. The total pumpage from the wells around the lake was about 15 million gallons daily in 1944. Of this quantity about 12 million gallons daily was taken from the Duhernal wells and the remainder from the wells north of the lake.

Before the completion of the Duhernal dam, an inspection was made of the proposed lake bottom to determine the nature of the surface material thereon and its probable effect upon recharge. A considerable part of the area now covered by the lake was flat and marshy. In some areas, particularly near the dam, there appeared to be one or two feet of black, peaty material above the sand. Toward the upper end of the lake, the patches of peaty material were not so thick. For more than half of its perimeter the banks are fairly steep, but in them sands of the Cape May formation or the Old Bridge sand are exposed at the surface.

Three streams flow into the lake, the Manalapan, the Matchaponix, and the Iresick Brooks. The two larger ones enter the lake at its southwestern extremity and the other from the southeast, not very far above the dam. The discharge from the lake is measured by a stream-gaging station at the dam. The flow of the tributary streams has been measured only occasionally,

and it is sometimes difficult to get satisfactory measurements of them. Several attempts have been made to measure the water flowing into and out of the lake, and thus to arrive at an estimate of recharge using evaporation figures obtained at the Perth Amboy Water Works. The resulting estimates of recharge range from 3 or 4 million gallons daily to as much as 8 million gallons daily. The results of one of the more reliable sets of measurements indicated a rate of recharge of about 5 million gallons daily in October 1943 or about 29,000 gallons per acre per day. This was about 35 per cent of the total pumpage from the wells around the lake at that time. There is probably

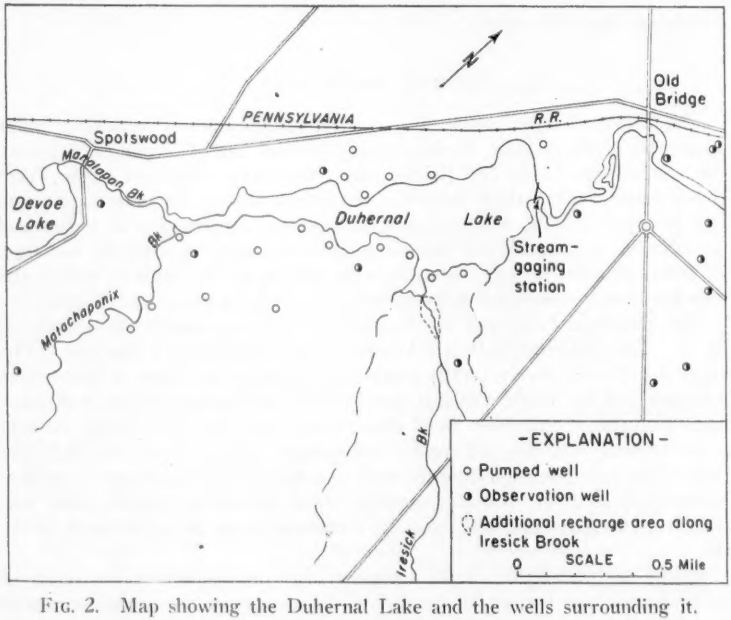

FIG. 2. Map showing the Duhernal Lake and the wells surrounding it.

some seepage into the lake from its banks, where no wells are near, but this could not be measured and would tend to make the results conservative. The actual rate of recharge in the parts of the lake nearest the pumping wells was probably considerably higher than the average. It is probable that a higher rate of recharge from the lake can be induced by the construction of additional wells around it and by pumping at rates which will cause a greater drawdown beneath it.

The streams entering the Duhernal Lake sometimes carry rather turbid water and it may be expected that the bottom of the lake will gradually be covered with silt. It is reasonably certain that up to the present time the rate of recharge from the lake has been increasing because of increased pumping

and greater drawdown rather than decreasing because of the deposition of silt. It is still substantially less than the average rate from the Runyon Pond which has been in existence more than fifty years, and in which no important dredging operations have been undertaken to remove silt for more than twenty years.

It is worthy of note that observations of temperatures in the water from the Duhernal wells have indicated wider seasonal fluctuations than is normal for the ground water in this area. This tends to confirm the conclusion that a substantial part of the water from these wells is derived from the lake. Attempts to evaluate this fact quantitatively, however, have not yielded satisfactory results. Comparisons of the chemical character of the water from the wells with that of the lake water have also been indicative of recharge from the lake, but the two waters are so similar that this method, also, has not yielded conclusive quantitative results.

The results of recharging the Old Bridge sand by spreading water in the Duhernal Lake have been so satisfactory that plans for additional water-spreading areas have been considered. The only part of these plans actually to be put into effect was the construction of a low auxiliary dam across Iresick Brook as indicated by dotted lines on Figure 2. When the flow of Iresick Brook is adequate to maintain the water level in this pond, it appears to add considerably to the recharge of the sand. It will be noted that one of the wells is almost directly between this auxiliary pond and the lake, and thus derives benefit from both. Some thought has also been given to the idea of diverting water from Matchaponix Brook or from a tributary thereof, into the area around the wells that are located between the Matchaponix and the Iresick Brooks. A little water has been diverted into this area experimentally with apparent good results, but no plans for permanent works have been made as yet.

PRINCETON.

For more than twenty years the Princeton Water Company has pumped surface water into a water-spreading area adjacent to the wells at its Stony Brook pumping station. The well field is situated on the west side of Stony Brook where it flows through a relatively narrow valley cut in the Stockton formation of Triassic age. The valley floor is almost level for a few hundred feet on either side of the stream. Logs of the wells at the pumping station indicate that there is a thickness of about 20 feet of detritus above the rock in the center of the valley. There is no evidence of any stratification, and the material at the surface is a fine-grained, silt loam and apparently not very permeable. The recharge area is covered by a rather heavy growth of shrubs and other vegetation so that the surface is perforated with openings that probably improve its capacity to absorb water.

The wells at this station draw their water from the Stockton formation, which consists of conglomerate and sandstone interbedded with red shale. None of these materials are very permeable in themselves but they have been extensively fractured so that the formation as a whole is fairly permeable. The water in this aquifer is transmitted almost exclusively through cracks

and fissures. Very little water moves through the pore spaces in the rock itself.

At first the water was pumped from the stream and spread over the surface by means of a temporary pumping installation. The results were so satisfactory that a permanent pump and intake have been established. It is now the practice to pump water intermittently at a rate of about 1,000 gallons per minute into the water-spreading area which covers several acres. When the area is filled to the overflow level, the pump is shut down until the water has percolated into the ground.

Probably one of the principal reasons that recharge is effective in this well field is the existence of an old ditch that was originally constructed across the valley for use as an infiltration gallery. This ditch was dug to the rock and filled with gravel and other porous material. It is probable that a considerable part of the water that reaches the rock travels through the permeable filling of this old ditch, and thus gains access to the rock at its surface where the cracks are most numerous.

No satisfactory measurements of the rate of recharge at this station have been made. The total pumpage from the station averages about 800,000 gallons daily, although in months of peak demand, it is about 1,200,000 gallons daily. The portion of this yield that is derived from artificial recharge is probably between 200,000 and 300,000 gallons daily. The average rate probably is in the order of 25,000 gallons per acre per day. Much of this undoubtedy enters the rock through the ditch referred to above and along the edge of the valley where the surficial deposits are thinnest.

LAKE MOHAWK.

The Lake Mohawk-Sparta Water Company at Lake Mohawk, New Jersey, uses an installation which is essentially the reverse of an ordinary infiltration gallery to recharge a shallow aquifer. The aquifer is composed of layers of sand and gravel in a filled pre-glacial valley. The lowest of these permeable layers is several feet thick and its bottom is about 30 feet below the surface. The others appear to be connected with it more or less indirectly, although they are separated from it by layers of clayey material in the immediate vicinity of the wells.

A trench, 3 feet wide and about 15 feet deep, was excavated and the bottom, 6 or 7 feet of it, was filled with 2-inch washed gravel. The layer of gravel was covered by a slab of concrete, and the remainder of the trench was filled with clay, which together with a layer of clay near the surface prevents the direct downward percolation of surface water into the aquifer. Through the top of the layer of gravel a porous pipe conducts water from the lake. This water recharges the aquifer and is withdrawn by a group of well points located a short distance from the trench, and having their screens in the lowest permeable layer. The well points were in use prior to the construction of the recharge works, but the storage capacity of the aquifer was insufficient to permit their continuous operation.

The total length of the recharging trench is a little more than 260 feet. The best information available indicates that the total rate of recharge is

probably not more than 100,000 gallons daily. The efficiency of this system is probably limited by the nature of the aquifer being recharged rather than by the capacity of the recharge trench to deliver water to the aquifer. The method may be of value in other localities.

EAST ORANGE.

Since 1937 the City of East Orange has operated several water-spreading basins to supplement the yield of the wells at their Canoe Brook pumping station. A description of this development has already been published.[2] It will therefore be described only briefly herein.

The wells at the Canoe Brook Station derive their water from beds of sand and gravel of Quaternary age in a buried preglacial valley. In the vicinity of the well field these aquifers are covered by a layer of dense, impermeable clay that was deposited at the bottom of a glacial lake. The sides of the pre-glacial valley are composed of rocks of Triassic age. The water-bearing beds crop out along the sides of the valley and farther upstream on its floor at elevations higher than the ground surface in the well field. Originally the wells yielded a substantial quantity of water by artesian flow. For many years, however, it has been necessary to pump them.

The recharging works are located on the outcrops of the aquifers where surface water is available for spreading. Three groups of small basins are located along the sides of the valley where the flow of tributary streams can be diverted into them. The total area of these basins and of the permeable parts of the channels leading to them is probably not more than an acre. However, some of them are located on very permeable material, and the recharge from them appears to be at a fairly high rate.

The major part of the water that is artificially introduced into the aquifers enters them through a large basin on the valley floor. This is known as the Meeker intake and has an area of eleven or twelve acres. Water is diverted into it from Canoe Brook which is the main stream in the valley, and a constant and substantial flow into the basin has been observed. Soon after its completion, the recharge from this basin was at the rate of about 2,000,000 gallons daily or about 170,000 gallons per acre per day.

A noteworthy feature of the recharge works at the East Orange Water Works is a system of mechanical controls that prevent the diversion of heavily silt-laden water into the basins. This is accomplished by gates that are arranged to operate automatically when the level of the water in the stream from which the water is diverted rises to a pre-determined level. In this way most of the flood waters are allowed to flow down the stream and their heavy load of silt is not deposited on the basins. Even at the lower flows, however, some silt is deposited. In 1945 after eight years of operation, the rate of recharge from the Meeker intake had decreased to about 130,000 gallons per acre per day. It is believed that by occasionally dredging or scarifying the bottom of the basin, its efficiency can be maintained at about its present rate.

[2] Roper, R. M.: Ground water replenishment by surface water diffusion. Jour. A.W.W.A., Vol. 31, pp. 165–179, 1939.

RECHARGE FROM EXISTING BODIES OF SURFACE WATER.

Closely related to artificial recharge are those instances where well sites are chosen to take advantage of potential recharge from existing bodies of surface water. Such recharge is not strictly artificial in the sense that the water is spread artificially over the intake areas of the aquifers. Nevertheless, the pumping of the wells does introduce an element of artificiality, inasmuch as it reverses the normal direction of the ground-water flow. In most instances under humid conditions, such as those existing in New Jersey, the ground-water is discharged and maintains stream flow during intervals when there is no precipitation. The establishment of wells reverses this normal

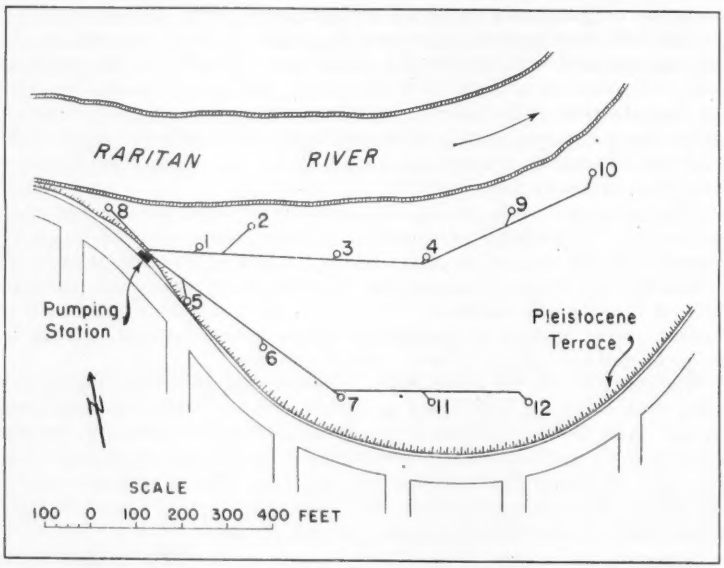

FIG. 3. Map showing the locations of wells at the Manville, N. J., Water Works

direction of flow and causes surface water to flow into the aquifer to supplement the suply from natural recharge.

In a few instances in New Jersey it has been possible to demonstrate this recharging action by measuring the loss in stream flow past the well field. However, there has seldom been an opportunity for demonstrating this type of recharge by tests on the wells themselves. Tests at the well field of the Borough of Manville provided an interesting exception to this rule. The conditions in this well field are shown on Fig. 3. The well field is located on the flood plain of the Raritan River which is bordered in this vicinity by a terrace of Pleistocene sand and gravel a short distance from the river. The

wells penetrate through the surficial deposits and draw their water from the fractured beds of the Brunswick shale of Triassic age. Two lines of wells extend downstream from the pumping station. One follows the river bank rather closely, and the other follows the foot of the Pleistocene terrace. All the wells are pumped by direct suction from the pumping station so that the drawdown in them is not very great.

During 1943 extensive housing developments were being constructed in Manville to care for personnel engaged in war work in the various industries in and near the borough. It appeared improbable that the existing public water supply of the Borough of Manville could take care of it without enlargement. Pumping and recovery tests were therefore conducted to determine how much additional water might be obtained from the well field and what extension thereto might be the most productive. The drawdown in the wells near the river was substantially less than that in the wells farther from the river and their recovery was much more rapid. Detailed computations based upon the results of the tests indicated that something like three-fourths of the water pumped from the well field was derived from the river. It was therefore concluded that additional wells could be drilled without overtaxing the capacity of the aquifer, and that the best locations for them would be near the river.

The water from Brunswick shale, like that from the Stockton formation, is derived almost entirely from cracks and crevices. The pore spaces in the rock itself are much too small to yield water freely. The results of several pumping tests on wells drawing from the Brunswick shale have indicated that this material has a fairly high coefficient of transmissibility but a low coefficient of storage. In fact the water stored in it is often not sufficient to maintain sustained heavy pumping throughout the intervals between periods of rainfall. Substantial yields of water are seldom obtained from it except in localities where the rock can be recharged continuously either from saturated porous surficial material or from bodies of surface water. The Manville well field is located between two such sources of recharge. However the results of the tests seem to indicate that in this instance, the river is much more effective than the sands and gravels in the terrace.

CONCLUSIONS.

The results obtained by water spreading for artificial recharging in New Jersey indicate that under favorable conditions such developments may be a valuable means of increasing the safe yield of ground-water supplies. Certain tentative conclusions may be drawn from the results that have been observed to date and consideration of them might lead to better success in similar developments.

Most of the successful developments have been in localities where the wells tap aquifers in their intake area so that water from artificial recharge can percolate rather directly down to the wells. In such cases the best results seem to be obtained when the water can be spread immediately adjacent to the wells, so that relatively little of the recharge water is lost by flow to other

parts of the aquifer. Conditions like those encountered at the East Orange Water Works where the water is confined in a definite channel are an important exception to this rule. In such cases the water derived from artificial recharge can be transmitted for considerable distances without danger of losing it by diffusion to other areas.

The deposition of silt in recharge basins has long been recognized as one of the major problems connected with developments of this nature. The decrease in the rate of recharge at East Orange from 170,000 gallons per day to 130,000 gallons per day in a period of about eight years, in spite of the use of regulatory devices to exclude the most heavily silt-laden waters, seems significant. Even more striking is the very low rate of recharge from the Runyon Pond when the level of the water in it is low and its area is limited approximately to the area that has been covered by iron oxide wastes from the filter plant. Nearly all this material was deposited within the last fifteen years. This seems to indicate that it is possible for some forms of sediment to destroy almost entirely the effectiveness of a water-spreading basin.

On the other hand the recharge from the Runyon Pond when it is essentially full at rates as high as 125,000 gallons per acre per day, suggests that the ordinary natural silting of a recharge basin may not entirely destroy its effectiveness. No part of the Runyon Pond or of the canal that was in use at the time that the measurements were made, had been dredged or scarified for about twenty years prior to the time the measurements were made. A considerable part of the pond had not been cleaned or disturbed in any way since its construction more than fifty years ago.

Much of the Runyon Pond when it is full is relatively shallow and supports a fairly heavy growth of vegetation. Each winter many of the plants die down and leave root holes penetrating the silt which might otherwise be relatively impermeable. In deeper water there is little growth of vegetation to penetrate the silt cover. If these observations relative to the probable effect of vegetation are correct, it would seem desirable to permit vegetation to grow in recharge basins even at the expense of higher water losses through evaporation and transpiration.

Even though the effect of silting may be lessened by the growth of vegetation, it may be so serious that every possible effort should be taken to minimize it. When feasible, automatic control works such as those installed at East Orange or desilting basins ahead of the recharge areas would seem desirable. Manually operated gates might also be effective if carefully attended. Scarifying, dredging, or scraping silt-clogged water-spreading areas will apparently partially restore their effectiveness, but ultimately these measures are probably more expensive and less satisfactory than works to exclude silt.

ACKNOWLEDGMENTS.

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U. S. GEOLOGICAL SURVEY,
TRENTON, N. J.
April 27, 1946.

NOTES ON THE ILMENITE DEPOSIT AT PINEY RIVER, VIRGINIA.

D. M. DAVIDSON, F. F. GROUT, AND G. M. SCHWARTZ.

ABSTRACT.

A drilling and trenching exploration of the ilmenite deposits at Piney River furnished maps and material for a re-study of the origin of the deposit. It seems to be a segregated dike intrusive into the earlier, closely related anorthosite. Later hydrothermal attack is widespread, but does not appear to have increased the percentage of titanium in the deposit explored. This leads to a discussion of the use of the term replacement, and some other terms, applied to ore deposition. If the terms are used carelessly or without adhering to the usual definition, the misinterpretations may cost later students much time and effort.

INTRODUCTION.

A COMMERCIAL problem in regard to the ilmenite property on Piney River, Nelson County, Virginia, led in 1944 to an extensive trenching and diamond drilling campaign [1] and some careful petrographic studies of the exposures and cores. The results gave somewhat different conclusions as to the origin of the ores from those of work by Ross,[2] and the difference is probably a result of different materials from those on which that earlier work was based. Ross studied a variety of deposits in outcrop, and when he saw the mine at Piney River it was much smaller than at present. Probably the evidence he reported applies to other deposits better than it does to that at Piney River. The present study, though brief, has the advantages of (1) large exposures in an open pit, (2) trenching and stripping of some critical areas in the extension of the ore body south of the mine, and (3) many drill cores in the ore and in the fresh rock below the ore.

THE FIELD EVIDENCE.

Fig. 1 shows the general location and relation of the deposit at Piney River. The ore is very much weathered, giving it an advantage over some richer ores, in ease of drilling, blasting, shovelling and grinding. On the other hand, weathering greatly complicates the petrographic and genetic study. Much of the ore is too friable to be broken into chips for grinding sections or polished surfaces. The petrographic work on partly weathered and fresh rocks, however, has been very enlightening.

[1] Davidson, D. M., Diamond-drill sludge sampling and appraisal of a weathered ilmenite ore body, Piney River, Virginia. Amer. Inst. Min. and Met. Eng., Tech. Pub. No. 1951, Feb., 1946.

[2] Ross, C. S., Titanium deposits of Nelson and Amherst Counties, Virginia. U. S. Geol. Survey P. P. 198, 1941.

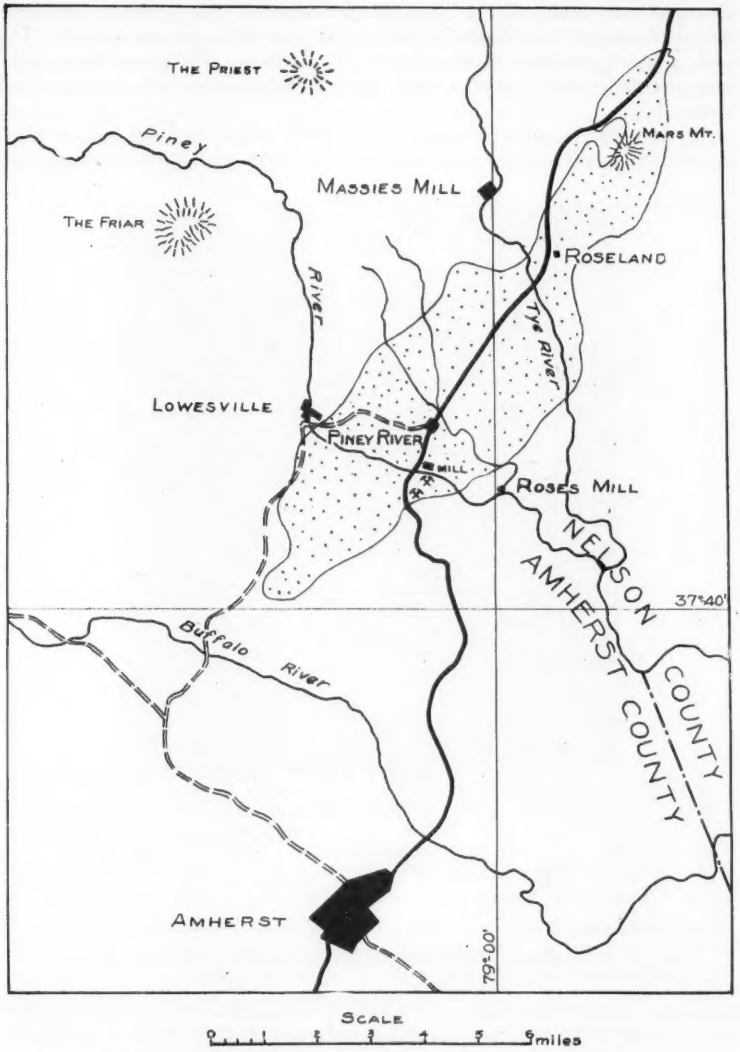

FIG. 1. Area of anorthosites (stippled) and location of ilmenite mine at Piney River, Amherst County, Virginia.

Fig. 2 shows that in plan the ore body is much elongated and fingers out locally into the wall rocks of "chlorite quartz gneiss" that seems to have been derived from the "anorthosite" of Ross—or "syenite" of earlier writers. The early papers gave general petrographic descriptions. The gneiss dips southeast, and the ore is a crudely tabular mass, largely conformable to the general structure.

In the open pit and trenches, as well as in the deeper material from drilling, there is a common alternation of layers (or banding) of slightly differing com-

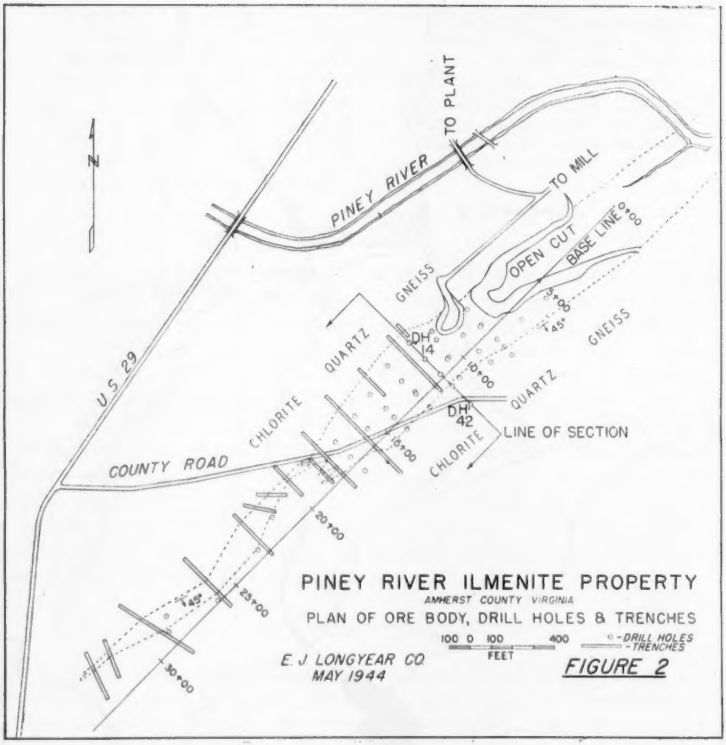

FIG. 2. Piney River ilmenite property, showing drill holes and trenches.

positions. Where these layers are especially feldspathic the crystals are platy and oriented in the same general plane as the major dimensions of the layers and of the ore body as a whole. The foliation based on the platy crystals, however, leads more definitely than the other structures to the inference that while the mass was crystallizing there was a motion that induced this orientation. It seems clearly to have been an intrusive magma motion, Fig. 3.

The orientation in some of the other rocks in the district is explained by Ross as a result of shear fractures in one plane direction and a replacement leaving feldspars in residual fragments between the shear planes. Some of the rocks collected in recent work on this Piney River ore body have no evidence of shear whatever, but are very fresh igneous rocks with minerals clearly oriented by motion of the magma during crystallization.

It is concluded that the ore came to place as a rather irregular dike. The dike seems to intrude and finger into the "anorthosite," and it may well be re-

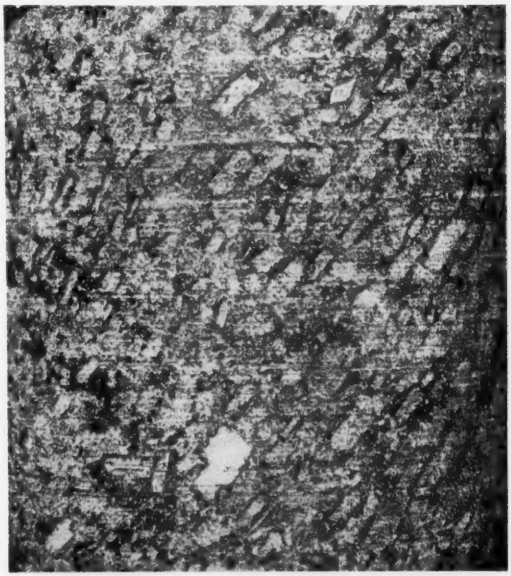

FIG. 3. Drill core of moderately fresh gabbro, showing feldspars oriented by flow. × 2.

lated to it about as Ross suggests;[3] "the anorthosite, the dikes, the parent abyssal rock of which they are offshoots, and the escaping solutions are all believed to be genetically related and to have been intruded without any great time intervals." We believe this statement should be understood to include the Piney River ore body as a dike, though there were later hydrothermal effects possibly from the same deep source.

PETROGRAPHIC EVIDENCES.

The petrographic data on which this preliminary statement is based are from rocks sampled in both trenches and drill cores. Most of the ore in the

[3] Ibid., page 18.

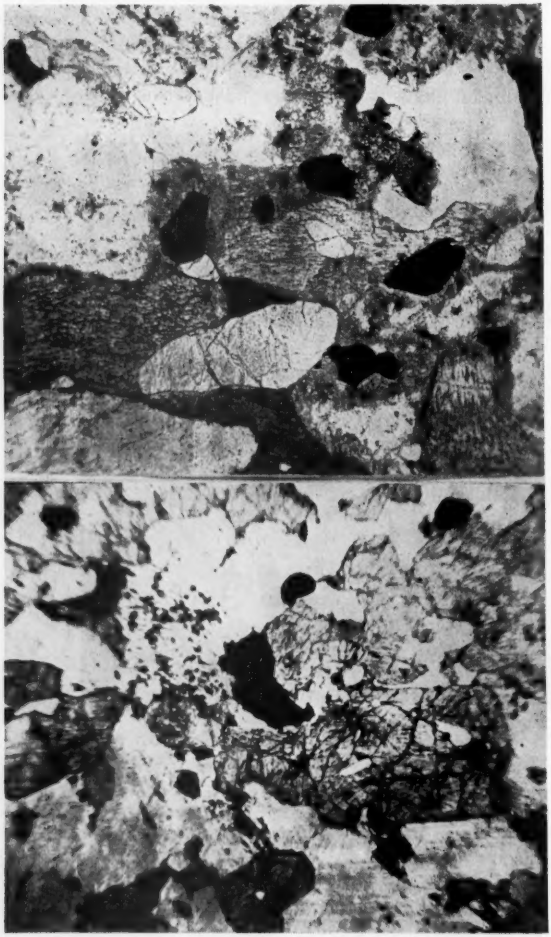

FIG. 4. Gneissoid gabbro; Labradorite, pyroxene, apatite, and ilmenite. No shearing. × 18.

FIG. 5. Slightly altered gneissoid gabbro or lean ore. Pyroxene (gray) has rims of hornblende (darker). Apatite and ilmenite are oriented and enclosed in primary pyroxene. × 35.

pit is so much weathered as to yield only indefinite evidence of the original rock. Pieces were selected on the basis of exceptionally fresh appearance in the midst of weathered ore. From these and the drill cores it is possible to select a series from almost perfectly unaltered to almost completely altered rock. Below the weathered ore there is much fresh material but the series here emphasized is closely associated with minable ore.

A specimen from drill hole 28, at a depth of 140 feet, is a very fresh gabbro, showing labradorite and pyroxene, with small amounts of biotite, ilmenite and apatite. No magnetite was detected in thin section. The orientation of grains is clearly shown in Fig. 4. The order of crystallization based on the usual criteria in igneous rocks is: (1) apatite, (2) ilmenite, (3) pyroxene, and (4) plagioclase. Only traces of dusty zoisite and kaolinite in the feldspar suggest alteration of any kind. Most of the pyroxene is a pale hypersthene, but there is associated augite.

This occurrence of ilmenite and apatite in fresh pyroxene in a fresh unsheared rock is to be contrasted with Ross's report [4] that ilmenite is "only with minerals that have invaded" pyroxene, chiefly hornblende, and "nowhere occurs in the unaltered portions." Ross agrees that apatite is earlier than ilmenite.

Polished surfaces of some of the ore that is richer in ilmenite and apatite than this fresh rock (from hole 5 at 115 feet and hole 41 at 190 feet) show some additional features. Some sulphide veinlets contain not only pyrite but pyrrhotite and chalcopyrite. Much of the ilmenite and apatite is in grains .5 to 1.0 mm. across, with the apatite slightly smaller and commonly earlier than the ilmenite. There are in a few samples some small grains of magnetite but in many samples magnetite is revealed only by high magnification of the polished and etched surfaces of ilmenite. At a magnification of 500 diameters the magnetite appears as fine black parallel lines up to an inch long and very narrow (Fig. 6). This is not a common pattern in magnetite-ilmenite intergrowths, and probably results when the solid solution is rich in ilmenite and the minor amounts of magnetite are oriented along ilmenite structure planes. The more common triangular pattern may result when magnetite dominates, and the octahedral magnetite planes control the position of minor ilmenite plates. Both are believed to result from exsolution from the cooling of a solid solution formed at high temperatures. This indication of high temperature origin agrees with the textural and mineral evidence of igneous origin of the ilmenite.

The included magnetite plates or rods probably account for the main part of the magnetism of the ilmenite grains, which serves a useful purpose in separations of the valuable minerals.

From drill hole 17 at 120 feet, and drill hole 25 at 101 feet come gabbros showing more apatite and ilmenite, and the beginnings of alteration of such rocks. The pyroxene has been attacked along its borders, forming rims of hornblende on pyroxene cores (Fig. 5). The orientation of primary minerals is clear and not related to fracturing or shear, of which there is little or none (Fig. 7). The alteration may have been a late magmatic reaction or deuteric

[4] Ibid., page 20.

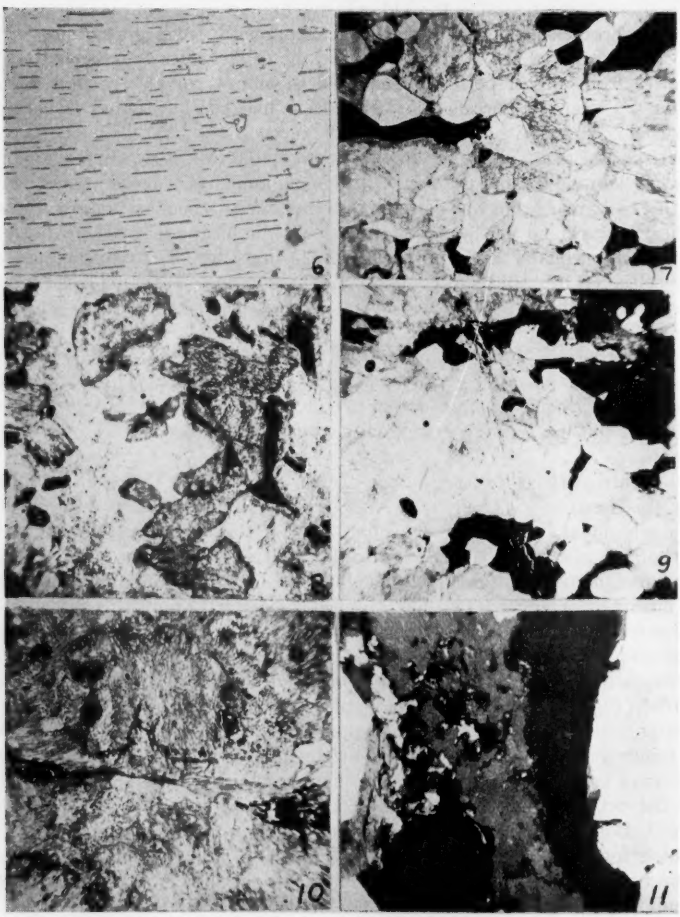

FIG. 6. Ilmenite in polished surface (white) with intergrown rods or plates of magnetite (black). × 330.

FIG. 7. Lean nelsonite ore showing fairly abundant oriented apatite and ilmenite, with gangue mostly hornblende and a little feldspar. No shear streaks. × 12.

FIG. 8. Gabbro in which ilmenite lies in hornblende aggregates, which are pseudomorphs after pyroxene. × 14.

FIG. 9. Lean nelsonite ore with gneissoid structure (right to left) crossed by a shear zone at about 70° to the gneissoid flow. Ilmenite is sheared, along with other minerals. × 10.

FIG. 10. Lean nelsonite with ore definite shear streak but widely disseminated alteration and granulation. Ilmenite is broken along with other minerals. × 100.

FIG. 11. Nelsonite crossed by pyrite (gray) which replaces ilmenite (black) rather extensively. × 240.

effect, but there is no evidence of large additions from the outside of the rock mass after it was solid rock. Some pyrite, associated with ilmenite, might suggest hydrothermal action but it looks just as primary as any early accessory mineral. In the sheared rocks noted in the following paragraphs there is much more pyrite and its occurence is sharply contrasted with the occurrence of pyrite here.

The drill core from hole 7 at depth of 117 feet and that from hole 8 at 25 feet show more extensive alteration. All the pyroxene is changed to amphibole (Fig. 8); but most of the amphibole is in pseudomorphs, the patches resembling the crystals of pyroxene in the fresh gabbro so clearly that there can be little doubt of their origin. In these rocks there is a little shearing, but there may still be a question whether the alteration made the rock more easily sheared, or the shearing made it easier for solutions to enter and alter the minerals. Apatite and ilmenite make up 15 to 20 per cent of the rocks—abundant enough to be mined as ore—but these minerals show no relation to shear streaks. The feldspars are considerably changed but they still retain their original forms. They are mostly andesine or oligoclase and have antiperthitic inclusions.

It is noteworthy that one thin section shows a hornblendic shear streak running irregularly across the rock in a general direction that is discordant with the orientation of primary minerals (Fig. 9).

The rocks with large amounts of ilmenite and apatite may be classified as "nelsonites." [5]

Progressively more shearing and alteration appear (Fig.10) in cores from hole 8 at depth 123 feet, from hole 21 at depth 90 feet, and hole 5 at depth 121 feet. As a final member of the series the rock from hole 26 at depth 88 feet is about 90 per cent al ered, leaving some apatite and ilmenite apparently residual from the primary minerals.

Fig. 10 shows that the effects of hot solutions are that apatite is corroded by the hydrous silicates; and Fig. 11 that pyrite is introduced replacing ilmenite. Such hot solutions do not leave any evidence that ilmenite was added from outside the rock, but on the contrary give much evidence that primary ores were being attacked. The rocks that are sheared show that ilmenite and apatite are sheared when the other minerals are (Figs. 9 and 10), contrasting in this respect with the rocks Ross described.[6] We find no rock at Piney River in which "ungranulated ilmenite and apatite are in thoroughly granulated rock," though Ross reports it as if characteristic of the whole district.

Ross [7] has not wholly ignored the possible origin of nelsonite as igneous dikes. He considers two theories of origin of the ores and rejects the theory of introduction of ilmentite by igneous intrusion because its "distribution seems to be in general controlled by shear zones." Since we find a fair percentage of ilmenite in unsheared rock we believe Ross chose the wrong alternative.

On the other hand we do not question his evidence that titanium minerals do replace some rocks in the district. Granted that there is replacement, there

[5] Watson, T. L., and Taber, S., Geology of the titanium and apatite deposits of Virginia. Virginia Geol. Survey Bull. IIIA, p. 300, 1913.

[6] Idem., pages 5 and 22.

[7] Idem., page 19.

is so little of it at the Piney River open pit that we estimate at least 90 per cent of the ilmenite was of primary igneous dike formation.

TERMINOLOGY OF IGNEOUS ACTION AND AFTER EFFECTS.

The terms used for stages of igneous action and its after effects are becoming greatly confused, and it can hardly be hoped that they can be wholly cleared up by this discussion incidental to a description of one ore body. This mass, however, is a commercial body and the terminology used in earlier discussions led to complications in the exploration and a very considerable expense. Possibly certain precautions should be taken in most discussions of such ores. If as we believe this ore is a dike, more or less altered, the terms used should indicate that origin clearly, and distinguish it from deposits formed by post-magmatic replacements. The economic geology of an igneous deposit, and that of a later replacement differ enough so that looseness or ambiguity in terms may lead to mistaken and costly inferences. Several terms are here selected for discussion and criticism.

A recent discussion by Shand [8] attempts to clear up the idea of stages of magmatic action and includes one post-magmatic stage. The stages may be left for further discussion elsewhere, but at Piney River it is of importance to distinguish rocks of really magmatic origin from those deposits resulting from emanations from the magma and post-magmatic action. The rocks formed by cooling magma should be named as igneous rocks; and the deposits introduced into rocks by emanations and by hydrothermal solutions should be distinguished. Since early descriptions [9] of nelsonites named them as igneous dikes, and Ross [10] carefully avoided the use of such terms, the mention of dikes in this paper requires justification.

In the first place let it be agreed that some of Ross's specimens and pictures show a good deal of evidence that rutile and possibly ilmenite have at places been introduced along fractures into the granulated "anorthosite." This is an important discovery, especially because some other men [11] had found that their field work indicated little transportation of titanium in gases or hydrothermal solutions.

This discovery, important as it was, seems to have led its discoverer to ignore all other possible origins for ilmenite in the district. Ross says,[12] "It is obvious that any explanation of nelsonite must apply to all types"; "all the minerals of the nelsonite have been formed by replacement of the anorthosite"; "the titanium minerals . . . are confined to the granulated portions"; "ilmenite is only with minerals that have invaded the clinohypersthene crystals and nowhere occurs in unaltered portions"; evidently not the result "of magmatic segregation."

[8] Shand, S. J., The terminology of late-magmatic and post-magmatic processes. Jour. Geology 52: 342–350, 1944.

[9] Watson, T. L., and Taber, S., Geology of the titanium and apatite deposits of Virginia. Va. Geol. Survey Bull. IIIA, page 101, 1913.

[10] Op. cit., pages 7–38.

[11] Lindgren, W., Concentration and circulation of the elements from the standpoint of economic geology. ECON. GEOL. 18: 423–424, 1923. Zies, E. G., The Valley of Ten Thousand Smokes. Nat. Geographic Soc. contributed Tech. Papers., vol. 1, No. 4, 1929; see page 15.

[12] Op. cit., pages 20 and 22; and abstract on page 1.

From our work we must protest that it is not "obvious" that one explanation for ilmenite formation must apply to all the ilmenite of the district. Ross's claim that "all the minerals" formed in a particular way implies that he saw all the deposits, which is unlikely. And finally we offer the descriptions and photographs of the preceding section to show that some ilmenite and apatite occur in fresh ungranulated gabbro, almost perfectly unaltered. It is rarely safe for any geologist to say what *did not happen,* unless his work is extraordinarily complete.

In support of our claim that some ilmenite is of igneous crystallization we add that it has in the gabbro (Fig. 4) no such associated hydrous silicates as Shand [13] has referred to as signs of hydrothermal attack (his stage 4), nor even the late magmatic silicates of his stage 3. The criteria for the end of magmatic action and beginning of hydrothermal attack have not often been critically discussed and are certainly not agreed upon by everyone. One can probably say, however, that chlorite is rarely if ever a primary igneous mineral. In absence of chlorite and other hydrothermal minerals, it may be hard to tell that any mineral is post-magmatic. Ross probably had in mind the supposed absence of any break between magma and hydrothermal solutions,[14] but the complete gradation is probably rare and occurs only in exceptionally deep-seated conditions.[15]

Segregation of ores is an expression widely used by economic geologists. In about 99 cases out of 100 the geologist who uses the term has in mind magmatic segregation—an accumulation of crystals, or sulphide fraction of magma, or gas reaction products, inside of the magma chamber. Ross [16] uses the term segregation in describing the formation of solutions from the parent rock, or parent magma, invading rocks, and mineralizing them—he speaks of segregation of mineralizers; and segregation by distillation. This may be justified by a dictionary definition of segregation, but is very confusing to one who has heard very little of any segregation except that within the magma, who has just read that the rocks are igneous, and who knows they are related to ores. Magmatic segregations are not distilled and do not mineralize other rocks. Ross says (page 34) ore minerals were "segregated from the parent magma during the earlier, hotter stages of the evolution of mineralizers." "Apatite . . . formed during the mineralization of the anorthosite." To write of "segregation from a parent magma" when thinking of an emanation from a magma (p. 37 says distilled over) is surely an entirely unnecessary confusion of our terminology.

Replacement, as used by Ross, seems to include many late magmatic or deuteric changes, which have in recent years been characterized as reactions with magma, and thus as "replacement only in a Pickwickian sense." [17]

[13] Op. cit.

[14] Ross, C. S., Physio-chemical factors controlling magmatic differentiation and vein formation. ECON. GEOL. 23: 864–886, 1924.

[15] Bowen, N. L., The broader story of magmatic differentiation briefly told. In Lindgren volume A. I. M. E., pages 106–128, especially 108–118, 1933.

[16] Op. cit., pages 15 and 37.

[17] Johannsen, A., A Descriptive Petrography of the Igneous Rocks, vol. 1, 1st ed., page 42, 1931.

Secondary, as used by Ross, seems to be based on the observation that a mineral is later than some other mineral. Most of us use the term to mean later than magmatic minerals. Few if any of Ross's "secondary" minerals, are so described as to demonstrate that they are not deuteric or late magmatic. Some are said to be introduced after granulation and shear, and are probably secondary as most geologists use the term; though when ilmenite is introduced into a granulated rock that had primary ilmenite there may be a question *how much* was introduced as solution and how much as magma. Ilmenite is so rarely transported by hot water that one should expect a high proportion of igneous rock ilmenite in such a mixture.

CONCLUSION.

The Piney River titanium deposit was in large part intruded as an irregular dike fingering into its walls. It has a primary gneissoid or flow structure based on oriented feldspars, apatite and other crystals. It was later sheared and hydrothermally attacked. Ross claims that much of the ore was deposited by the post-magmatic fluids, but in the weathered material now mined it is probable that titanium was formed mostly in small segregated bands or segregated dikelets. The late hydrous magma probably caused deuteric changes, forming hydrous minerals; and hydrothermal attack carried the changes farther and replaced some of the ilmenite by pyrite. It may even be that the hydrothermal action reduced the grade of titanium ore by adding water and sulphur, more than it enriched it by adding titanium. Weathering has improved the workability of the ore.

TECHNICAL APPLICATIONS.

The Piney River titanium first considered a dike and then a replacement, is now believed to be a dike-like intrusive related to "anorthosite." Here is an example where partial data led a geologist to suggest that older ideas of origin were incorrect. The facts of replacement need not be questioned, but those facts give no proof that the main development of ore was a result of that replacement. If the ore of a dike is slightly modified by replacement, any great emphasis put on replacement processes is so misleading that it is enough to cost later students much time and money.

So far as the replacements result from a reaction of a late magma—as distinct from hydrothermal attack and additions—they would better not be called replacements at all. The more definitely hydrothermal replacements should be judged quantitatively to see if they are significant in ore formation. In this example they probably reduced the grade of ore rather than forming or enriching ore. They seem to have softened the mass so that the ore is cheaply mined and concentrated. The miners experience with igneous dikes, even those with deuteric changes, indicates much more continuity and "depth extension" than can be expected of hydrothermal replacements.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
May 14, 1946.

A CORRECTION FACTOR FOR SPECIFIC GRAVITY AND VOLUME DIFFERENCES IN FRAGMENT ANALYSIS.[1]

FELIX CHAYES.

ABSTRACT.

Two methods for determining average grain weights of sized particles are described, and average weights obtained with one of them for 100–200 mesh fractions of 16 common minerals are given. It is shown that reliable values for mica will require a micro-weighing for each analysis. Practical examples are used to illustrate the inadequacy of specific-gravity correction and the need for a combined specific-gravity and volume correction.

INTRODUCTION.

In two previous papers[2] the writer has described sampling and counting procedures by which number frequencies of known precision may be obtained from sized granular samples. The second paper contained also a brief treatment of the potential accuracy of the method, but readers were cautioned that these remarks were intended to apply only in the absence of "shape" (more properly, volume) differentials between the phases being counted.

In many applications of fragment counting the number frequencies need not be converted into weight percentages. Until recently, such applications have accounted for most of the fragment counting performed in connection with purely geological studies. Much of the work done in industrial petrography also falls in this class, even though the industrial petrographer usually thinks of and reports his results in terms of weight. In comparing the efficacy of different treatments or reagents on an ore it is of no consequence whether petrographic results are reported as weight or number percentages, provided all results are given in the same way.

But if the ore is amenable to beneficiation the mineral dresser will one day produce a tailing and a concentrate for which he will require weight compositions on which to base his cost estimates. These samples the petrographer must pass along to the chemical laboratory unless he is prepared not only to think of but actually to estimate composition in terms of weight.

This paper discusses the problem of converting number frequencies into weights, offers two simple methods appliable to a wide range of granular materials, and lists some weight corrections obtained with one of them. It concludes with a few practical illustrations selected to emphasize the importance which may attach to these results in critical samples.

[1] Published by permission of the Director, Bureau of Mines, U. S. Department of the Interior.

[2] Econ. Geol., Vol. XXXIX, No. 7, 1944, pp. 484–505.
" " Vol. XL , No. 8, 1945, pp. 517–525.

PREVIOUS STUDIES.

Questions concerning the shape, roundness, sphericity, etc., of mineral particles have been discussed by many geologists in recent years, but most of these studies deal with the shape itself rather than its relation to weight. An admirable review of the subject with full bibliography is given by Krumbein and Pettijohn.[3]

The characterization of shape is in itself a complicated and as yet not satisfactorily solved problem, and the procedure used here is simply to bypass it, following a suggestion first offered by Grout.[4]

Grout mixed equal weights of sized biotite and garnet on a slide and determined their relative frequencies by counting. Where mica is involved, not only its relative weight but also its absolute weight and the volume of the final mount strongly influence the observed frequency.[5] But the method described in the first part of this paper and used to obtain the values shown in Table 1 is essentially an expansion of Grout's suggestion.

EXPERIMENTAL DESIGN FOR AVERAGE SIZED-PARTICLE WEIGHT DETERMINATIONS.

The actual distributions of shape and volume in grains of a sized fraction must be very complex and will undoubtedly vary with the mineral as well as with the crushing and sizing operations to which it is subjected.

But the grains of any fraction, sized or unsized, are characterized by some average weight, and if each mineral is subjected to a standardized grinding and screening these average weights will be at least theoretically comparable with what would be expected if two or more minerals had been mixed and ground as a single sample.[6]

If W_1 and W_2 are the average grain weights of two minerals and F_1 and F_2 are the number frequencies of the minerals obtained by fragment analysis of a sample, the weight ratio of the two in the sample will be:

$$\frac{W_1F_1}{W_2F_2} = \frac{m_1}{m_2}, \tag{1}$$

where m represents the actual weight of each constituent in the sample.

Using W_1 as a standard of unit average weight and solving for W_2:

$$W_2 = \frac{F_1m_2}{F_2m_1}. \tag{2}$$

[3] W. C. Krumbein and F. J. Pettijohn, Manual of Sedimentary Petrography, Appleton-Century, Chapter II, 1938, pp. 227–302.

[4] F. F. Grout, Accuracy of accessory mineral methods, Report of the Committee on Accessory Minerals, National Research Council, Division of Geology and Geography, 1937, p. 26.

[5] It should be pointed out, however, that Grout's test was made simply to estimate ". . . the order of magnitude of the error likely to occur because of cleavage" and his conclusion is that "Two workers without special precautions are not likely to obtain concordant results with such minerals."

[6] The assumption here is that the effect of grinding together constituents of greatly differing hardness will express itself largely or entirely in differences between rather than within size-fractions. It is common knowledge that hardness (or grindability) differences are in fact strongly reflected by differences in composition between the various sized fractions, and the assumption that this is their principal effect seems justifiable if the sizing intervals are sufficiently small. Experimental investigation of this problem would be difficult but useful.

The F values are determined by analysis of a binary mixture made up with known weights (m) of the two minerals, and the resulting W_2 is an average sized-particle weight against W_1 as standard.

Equation (2) may be written

$$W_2 = \frac{F_1/m_1}{F_2/m_2} = \frac{n}{d} \tag{3}$$

and its error (E) will be propagated as that of two quotients combined to form a third,[7] or

$$E_{w_2} = \frac{1}{d}\sqrt{E_n^2 + \frac{n^2 E_d^2}{d^2}}. \tag{4}$$

Errors in the frequencies may be computed directly from the data or obtained from the previous paper on sampling error (2—p. 517 et seq.). Using King's Mountain (N. C.) spodumene, against Acworth (N. H.) beryl as standard, for example, the data are:

Mineral	m, in mg.	E_m, in mg.	F	E_F in p.p.t.
Beryl	396.8	1.0	585	2.2
Spodumene	381.1	1.0	415	2.2

Ten analyses of this mixture were made, the average of all ten being used for F. The standard error of the group was used as the error of the frequency, and a weighing error of 1 mg. in each m value, which seems a generous estimate, was assumed. Entering equation (4) first for n and d separately and then for their quotient gives

$$E_d = E_n = 0.007$$
$$E_w = 0.011.$$

From equation (2) W_2 is 1.356; the error is thus about 0.8 per cent, and the estimate should be stated as 1.36 ± 0.01. As the duplicate values in Table 1 indicate, results well within this estimtae of error can be easily obtained. Ratios of good determinations made on the Jolly balance may be in error by as much or more, and certainly there is no comparison between the precision of specific weights and that of the too frequent though sometimes unavoidable practice of picking specific gravities from text or reference books. On the ground of precision alone the method is thus at least comparable to those now in use. Its real superiority, however, rests not in precision but in accuracy, as shown in the following discussion.

PROCEDURE AND RESULTS.

Crushing and Sizing.—The effects of different methods of crushing and sizing on average particle shape and volume are probably slight, but since they

[7] T. B. Crumpler and J. H. Yoe, Chemical Computations and Errors, John Wiley & Sons, p. 178, 1940.

are unknown the procedure actually used is described in detail. This procedure was adopted primarily because it requires no special equipment, and the results may thus be readily checked by interested petrographers. But an almost equally important advantage is that rather small amounts of a mineral —of the order of 30 to 50 grams—are sufficient; even with the common minerals surprising difficulty was experienced in obtaining as much as a hundred grams of satisfactory purity.

The sample was first crushed by hammer or in a large iron mortar to about ¼″ size and carefully graded under a binocular microscope. Impure pieces were discarded, and the remainder was *crushed* (not ground) in the same mortar. No more than 10 to 15 grams were introduced into the mortar at one time, and after 8 or 10 blows the contents were poured onto a 28-mesh screen. Oversize was returned and new material added to the mortar, and the process was continued until all the powder passed the screen.

It was then shaken for 30 minutes on a Ro-tap in a nest including 35-, 65-, 100-, and 200-mesh screens. The 100- to 200-mesh fraction, which was to be used in the tests, was cleared of magnetic iron with an alnico magnet and thoroughly washed to remove slimes. It was then brought to dryness over a water bath or open flame and kept in an oven at 110° for at least an hour.

The washed, iron-free fraction, usually weighing 8 to 15 grams, was next poured through a 10-mesh screen about 50 times to eliminate size segregation introduced by the washing process. This method of mixing proved more satisfactory than the usual rolling, whether on rubber or in a bottle. A small semicircle of screening was fitted into the top of each of two 50-ml. beakers, opposite the lip. The powder was poured back and forth from the lip of one beaker onto the screening set in the other.

Preparation and Analysis of Binary Mixtures.—About half a gram was cut from the unknown with the microsampler; weighed to the nearest 0.1 mg., and left on the balance pan. A sample of about the same size was cut from the beryl standard and added to the unknown, and the mixture was weighed, the difference being recorded as the weight of beryl. It was then transferred from the pan to one of the sifting beakers and subjected to the same mixing process used in preparing the pure materials. It was then reweighed, and discarded if the weight loss seemed excessive; a weight loss of 4 mg. per gram was sufficient ground for rejection. In only a few instances were losses of as much as 3 mg. tolerated, and nearly all were less than 2.5 mg; even if a loss of this magnitude was strongly differential, which was not usually the case, its effect on the result would be negligible.

From the reweighed mixture at least 5 and sometimes more microsamples were split, mounted, and analyzed. The weights and average frequencies were used for the computation indicated by equation (2). The average standard error of the mean frequency values for all determinations shown in Table 1 was a little less than 3 parts per thousand. Count groups with standard error of more than 7 parts per thousand were discarded.

Average Specific Weights of Some Common Minerals.—Table 1 lists the determinations so far completed. Specimens 5, 8, 11, and 13 were obtained from the study collection of the United States National Museum; the rest are

from the Bureau of Mines collection at College Park, Maryland. No. 2 was ground in a pebble mill, and the grinding history of Nos. 9 and 10 is unknown. The remaining specimens were prepared as described in the section on "Crushing and Sizing."

TABLE 1.

AVERAGE SPECIFIC WEIGHTS OF SOME COMMON MINERALS.

	Mineral	Locality	Specific Weight
1	Beryl	Acworth, N. H.	1 (assumed)
2	Beryl	Wakefield, N. H.	1.00x *
3	Quartz	Acworth, N. H.	0.96
4	Albite	Bancroft, Ontario	0.80
	"	" "	0.81
5	Cleavelandite	Amelia, Va.	1.02
6	Spodumene	Kings Mt., N. C.	1.36
7	Spodumene	Harding, N. M.	1.40
8	Actinolite	Spruce Pine, N. C.	0.93
9	Kyanite	India (massive)	1.17
10	Kyanite	Celo mine, N. C.	1.07
	"	" " "	1.07
11	Calcite	Mena, Ark.	1.11
12	Corundum	Buck's Creek, N. C.	1.44
	"	" " "	1.45
13	Garnet	Wrangel, Alaska	1.22
	"	" "	1.22
14	Garnet	Gore Mt., N. Y.	1.29
15	Fluorite	Sheridan, Ky.	1.39
16	Galena	Patagonia, Ariz.	2.92

* Run against Acworth quartz.

PRECAUTIONS.

In a long series of manipulations such as that just described it is, of course, necessary to use considerably more care than is required for routine analysis. Beyond this, however, there are three trouble spots that require special attention.

It is extremely important to remove undersize powder from the sized pure mineral fractions, because the slimes are greatly concentrated by the microsampling process. The sand as taken from the 200-mesh screen is washed by repeated decantation; before each pouring the contents of the beaker are thoroughly stirred and then allowed to stand. A standing time of 1 to 2 minutes will permit all but the fines to settle if the volume is made up to about 200 c.c. in a 250-c.c. beaker. The washing is continued until the supernatant liquor is clear. Drying may be done over an open flame if time is short, but splattering must be avoided; a water bath is preferable. In either case the sample is next oven-dried for at least an hour at 110°.

Weight loss in the desliming process should not exceed 5 per cent and in most instances will not be much above 3 per cent. Losses in excess of 5 per cent may be attributed either to incomplete screening, overvigorous decantation, or splattering during drying. Results based on samples showing large weight losses during desliming will always be doubtful; it will save time and eliminate uncertainty to discard such samples.

Incomplete delivery from the sifting beakers is a constant source of trouble. To overcome this difficulty the beakers are occasionally filled with an alcoholic

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solution of lauryl-amine hydrochloride (10 drops in 100 c.c.) and allowed to stand for 15 or 20 minutes. They are then permitted to dry in air or else placed in a low-temperature oven (50–60°). After drying they should be gently polished with a clean towel.

Certain minerals continued to stick even after the beakers had been treated, and it was necessary to condition and coat the minerals rather than the beakers.[8] The results are sometimes striking. In one test the smallest loss in sifting before treatment of the minerals was 14 mg. in a 1-gram sample. This was a beryl-quartz mixture; after each of the minerals had been conditioned and treated with lauryl-amine hydrochloride the sifting operation on a new sample of about the same size was accomplished with less than 2-mg. loss.

Whether the beakers and minerals are conditioned or not, it is usually necessary and always desirable to use a brush on the beakers just as one uses a rubber-policeman in transferring precipitates. It may seem pointless to bother about conditioning if a brush is to be used in any case, but if the minerals have a strong tendency to stick to the glass the brush will not help much in removing them.

Finally, considerable difficulty was caused by segregation in the index liquid when the constituents differed greatly in specific gravity. This type of segregation has been known in our laboratory for many years and should have been mentioned in previous papers. The remedy is simple. Instead of counting only a fixed number of grains, the operator should traverse the entire slide; the traverse interval may be broadened to avoid an overextended count. For samples in which segregation is pronounced the results will then be comparable to those given by fixed-length counts on unsegregated material. Evidence accumulated during the work reported in this paper suggests that results based on traverses made over the entire slide are slightly superior to fixed-length counts even in the absence of visible segregation, but the difference does not seem large enough to be worth measuring.

DESIRABLE PROPERTIES OF STANDARD MINERALS.

A good standard should be characterized by:

1. Ease of identification, whether by color, refractive index, shape or birefringence.
2. Specific gravity not very different from those of the minerals against which it is to be run.
3. A weak or easily corrected tendency to adhere to glass or paper, as measured by weight losses on pouring or mixing.

The first two properties are purely relative, and the first in particular is a *sine qua non* of good work. Traversing the entire slide will yield acceptable

[8] The writer is indebted to Mr. Foster Fraas for the suggestion which led to the use of the alcohol solution on the beakers and to Messrs. Fraas and Frank Lamb for information on the conditioning and coating of minerals. Interested readers should consult O. C. Ralston, Flotation and Agglomerate Concentration of Non-Metallic Minerals, U. S. B. M. Rept. Inv. 3397, 1938, A. F. Taggart, *Handbook of Mineral Dressing*, Section 12, John Wiley, 1945, or other references.

results as long as the specific-gravity difference is moderate and sometimes even if it is rather large. Transfer of the microsample to the index liquid can scarcely be accomplished without some loss due to splattering, however, and where the specific-gravity difference is extreme this loss will be mostly or entirely of the lighter mineral; the average grain weight of the heavier constituent may therefore be underestimated.

Standards should be established for at least two and preferably for three levels of specific gravity. These should be run against each other with large numbers of replicate analyses.

A strong tendency to adhere to glass or paper will render unsatisfactory a standard that may otherwise be highly desirable. Very little is known of this property, and it seems to vary widely with temperature and humidity; most trouble has been experienced in very dry weather or when minerals have been heated for long periods, even at low temperatures. The repeated pourings required by the mixing procedure sometimes reduce the tendency to stick. An explanation in terms of surface charges is indicated, but in the absence of other methods the petrographer is forced to make his selections by trial and error, mostly the latter.

In closing this discussion it may be pointed out that the grinding or crushing history of a potential standard is of no consequence. Since the effect of different size-reduction methods on the relation between grain diameter, shape, and volume is largely unknown, adoption of standards requiring neither crushing nor grinding might prove advantageous; glass sands, heavy mineral concentrates from beach sands, metal shot, and glass beads should all be considered.

DIRECT DETERMINATION OF APPARENT GRAIN WEIGHTS.

The method already described involves two weighings and two frequencies for each determination. Its principal disadvantage is that proper mixing of the constituents, without which good results cannot be obtained, requires a great deal of handling. This not only introduces chance for error, but it makes localization and control of the error difficult or impossible. Either of the weighings may be at fault, the sifting of the pure minerals or of the mixture may have been inadequate, or the inevitable losses incurred in sifting the mixture and in transferring the microsample to the index oil may have been strongly differential. With proper precautions the method nevertheless yields surprisingly good results, but one requiring less manipulation would be theoretically if not practically superior.

A fragment count may be interpreted in terms of frequency per milligram of microsample without reference to the main sample. If the average number of grains counted per milligram could be determined for each of a series of minerals, the results could either be used directly as average frequencies or converted into average grain weights.

Weighings of milligram quantities are easily and quickly made on a Roller-Smith microbalance. The 5-mg. model available in our laboratory is equipped with a hopper-like pan hinged at one side of the top and emptying through the bottom. The application of this balance to the problem is almost self-evident.

The pure mineral is sifted as before; a sample of less than 5 mg. is split from it with the microsampler and weighed. A slide carrying a drop of the proper index liquid is held an inch or so below the pan, and the hopper is tripped, pouring the sample into oil. Sample and liquid are mixed with a glass rod, a cover slip is applied, and the mount is subjected to a count made at 1-mm. (or any arbitrary) interval over the entire surface. The weight of the sample divided by the total number of grains counted is an estimate of the average apparent grain weight; the reverse calculation is an estimate of the average number of grains counted per milligram. The same-diameter cover slip, the same traversing interval, and as nearly as possible the same volume of index oil must be used for each determination.

This method is potentially superior to the relative-weight determinations made with an internal standard, because each value is the quotient of a single weighing and a one-constituent count, and the most troublesome step in the mixing process is eliminated. With further development it probably will replace the original method in our laboratory. In practice, however, the transfer of microsample from balance pan to index oil is still unsatisfactory; this combined with the small capacity of the balance renders the results far less precise than those obtained from binary mixtures. The standard errors of frequencies per milligram are of the order of 2.5 to 5 parts per hundred, whereas average frequencies obtained by the other method were discarded if they contained errors in excess of 7 parts per thousand.

Results from both methods are comparable, however; for example, the grain-weight ratio of quartz and Celo kyanite as obtained by the direct method is 1.08, and the quotient of the entries for these two minerals in Table 1 is 1.11. The new method clearly requires and deserves further study. It is mentioned here because of information it has already yielded concerning the problem of counting mica, described in the following section.

COUNTING MICA.

The difficulty experienced in counting mica led to the use of weighed microsamples, though for the sake of clarity the order of description has been reversed. It had been expected that the average grain-weight correction for muscovite would be large, as it of course proved to be. A binary mixture containing 12.8 per cent muscovite and 87.2 per cent calcite was analyzed five times, yielding an average relative frequency of 32.6 per cent for the muscovite. But the individual values ranged from 27.6 to 41 per cent, a spread much greater than any encountered in previous work.

A series of microsamples containing varying amounts of muscovite and calcite was then made up. These ranged in total weight from 4 to 6 mg., and in mica content (by weight), from 2 to 70 per cent. Each microsample was subjected to a single count, made at 0.5-mm. traverse interval because of the small size of the samples.

The quotient $\frac{\text{total frequency of calcite}}{\text{weight of calcite}}$ was reasonably constant in each sam-

ple, its average value being 136 grains per milligram, with a standard error of 1.9 grains.

The ratio of grains counted to microweight of muscovite was far from constant, however, and the data for each sample are shown on a log-log grid in Fig. 1. The regression of total frequency on microweight is:

$$\text{Log } y = 2.21283 + 0.72689 \log x, \text{ or approximately,} \quad (5)$$

$$y = 163x^{0.73}, \quad (6)$$

where y is the total frequency of mica and x is the weight of mica in tenths of a milligram.

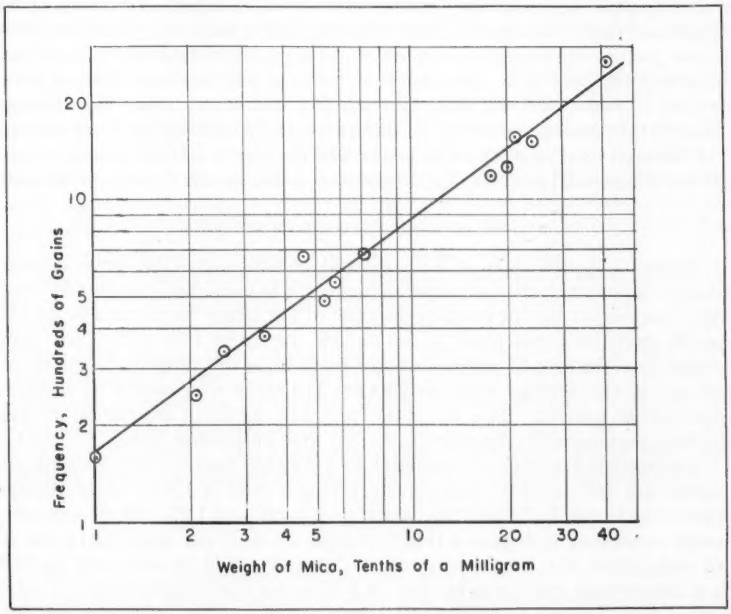

FIG. 1. Total frequency of mica as a function of milligrams of mica in the mount.

The basis for the criticism of Grout's mica-garnet experiment will now be clear. The apparent frequency of mica is not a matter of its weight percentage in the macrosample but rather of its actual weight in the microsample as related to the volume and surface area of the mount. The surface area of the mount is adequately controlled by the the diameter of the cover slip. That no special measures are required to control volume is indicated by the almost negligible residual dispersion shown by the experimental points (the index of correlation is 0.99 +). Evidently the main source of this systematic error is the weight of (or number of grains in) the microsample, and unless this is

either measured or held constant in each analysis the actual mica frequencies mean very little.

If a microweighing step could be inserted in routine analysis, there is every reason to believe that number frequencies of mica and other flaky minerals could be satisfactorily converted to weight percentages. In the absence of such a step these minerals should either be eliminated or ignored. Many micas can be removed by sifting on glazed paper, and others will respond to heavy-liquid or magnetic separation; where no separation can be effected fragment counting should be used only to determine the ratios of nonmicaceous minerals to each other.

The simplest explanation of equations (5) and (6) is that when the mica grains become numerous they arrange themselves in layers and that only the uppermost flakes are observed and tabulated in the analysis. That the effect is real and strong enough to require consideration is established beyond reasonable doubt by Fig. 1. It should not be expected, however, that all micas or even all muscovites will obey equation (6), and it may prove that the constants in the equation vary even for different size-fractions of the same mineral. The material used in these experiments was the 100 to 200-mesh fraction of a ground commercial product; the sample was shaken on the Ro-tap for an hour.

IMPORTANCE AND UTILITY OF RESULTS.

A specific-gravity range of 2.5 to 4.1 will include most of the common transparent minerals whose quantitative estimation is likely to be attempted by fragment analysis, so that in practice the ratio of the larger to the smaller of two specific gravities is not likely to fall outside the range 1 to 1.64. Any ratio formed from the first 15 entries in Table 1 will lie in this range; it might therefore appear that average grain weights are just about what would be expected from specific gravity. This is not the case, and uncritical application of even the best specific-gravity determinations may give misleading results.

The specific gravities of specimens 13 (Wrangel garnet) and 3 (Acworth quartz) are 4.07 and 2.65, respectively, giving a ratio of 1.54. Their average grain weights are 1.22 and 0.96, which give a ratio of 1.27. If an unknown sample containing both gave a relative frequency of 30 per cent quartz and 70 per cent garnet, the weight percentage of garnet would be estimated as 74.7 from the average grain weights and 78.3 from the specific gravities. A mixture of Celo kyanite and Acworth quartz which yielded equal number frequencies of each mineral would actually contain 52.7 per cent kyanite by weight, while an estimate based on specific gravity could not be less than 57.2 per cent and might be considerably more. Good quantitative analysis of major constituents evidently requires proper average grain-weight factors if the results are to be converted to a weight basis.

Fragment analysis has not been widely applied to the estimation of major constituents in rocks, but at least one such application in this country has been published,[9] and in Europe the method seems to be undergoing independent development.[10] Its use may be expected to increase in the near future, particu-

[9] Jaffe, H., Journal of Geology, Vol. LIV, 1946, p. 105.
[10] Sahama, Th., Compte Rendus Soc. Geol. de Finlande, Vol. XVIII, 1945, p. 27.

larly in the study of coarse-grained or oriented rocks. But the real need for the method in our laboratory arose in connection with what may be called the "critical" samples in beneficiation tests, the two which the mineral dresser hopes are his final tailing and final concentrate.

Suppose, for example, that a quartz-garnet product yielding a number frequency of 3 per cent garnet has been obtained and that economic considerations require a garnet content of not more than 4 per cent in the tailing. Using the figures in Table 1, the weight per cent of garnet will be estimated as 3.8, whereas specific-gravity correction alone would indicate that the weight per cent of garnet was 4.6. In one case the beneficiation is satisfactory; in the other the tailing must be retreated. Similarly, a number frequency of 3 per cent kyanite in a kyanite-quartz mixture would indicate 3.3 per cent kyanite by weight if average-weight corrections were used but a minimum of 4.0 per cent based on specific gravities.

For most of the entries in Table 1 the average grain weight is less than would be indicated by specific gravity. For the Sheridan (Ky.) fluorite as well as for both the North Carolina and New Mexico spodumenes the situation is reversed, while for Buck's Creek corundum there is very little difference between the two values. With spodumene, for instance, in a quartz-spodumene mixture, a number frequency of 3 per cent would represent 4.3 per cent by weight, while the highest possible value for specific-gravity correction alone would be 3.8, and a result greater than 3.6 is quite unlikely.

Enough has been said to indicate that good quantitative work, whether on major or minor constituents, requires adequate correction factors and that whether or not a correction is required must be determined in each specific case. Although the effect of different size-reduction methods on the relation of grain diameter, shape, and volume is unknown and may remain unknown for some time, it should be possible for interested petrographers to develop corrections based on crushing and grinding standardized according to their own needs and facilities. The information thus accumulated would soon show whether and how a separate study of grinding effects should be undertaken.

CONCLUSIONS.

Frequencies obtained by fragment analysis of samples of unknown composition cannot be accurately converted to a weight basis unless information is available concerning not only specific gravity but also average grain volume of each constituent. The procedures described here lead to average grain weights which include both these factors. Specific gravity may, of course, be determined separately and its influence eliminated from the weight factor. Such a development would permit a novel and perhaps very useful approach to studies of grain volume and surface area. But for analytical purposes it is more convenient to combine the effects of specific gravity and grain volume in a single correction, and an experimental procedure that yields direct weight factors is preferable.

Results for 16 common minerals do not lend themselves to ready generalization. With beryl as standard, the average grain weight is usually somewhat

less than specific-gravity relations would suggest; in a few instances, however, it is considerably more, and in a few others there is no need for other than specific-gravity correction. Except for the fact that grain-volume differences are so far invariably smaller than specific-gravity differences, neither the size of the weight correction nor its relation to the specific-gravity ratio can be predicted from crystal system, cleavage, hardness, or other mineralogical properties. The influence of grinding and sizing procedure on the weight correction, though probably slight, is also unknown.

The values shown in Table 1 indicate that the size of the average grain-weight correction must be determined in each case, but with the methods described these determinations may be made by any competent petrographer. Data accumulated by many petrographers over a period of years may one day permit a more general treatment of the problem. But regardless of the possibility of more satisfactory generalization, the method of binary mixtures may be usefully applied, as it stands, to the innumerable specific analytical problems confronting the modern petrographic laboratory.

ACKNOWLEDGMENTS.

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This investigation was conducted under the general direction of J. B. Zadra, Chief, College Park Division, and the immediate supervision of Alton Gabriel to whom the writer is indebted for valuable criticism and advice. Several of the mineral specimens used were obtained from the National Museum study collections, through the courtesy of E. P. Henderson. Information on conditioning and coating of minerals was generously supplied by F. Fraas and F. Lamb, both of the staff of the College Park Division, Metallurgical Branch.

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THE PUNCHED CARD IDENTIFICATION OF ORE MINERALS.[1]

ERNEST E. FAIRBANKS.

ABSTRACT.

A punched card system has been developed for the identification of ore minerals, especially the fine intermixed and disseminated forms of most ores. The variation of chemical and physical properties introduces a sufficient number of possible permutations to warrant use of the identification aid. Details are given for the preparation of a set of determinative cards. A brief evaluation of certain determinative data has been attempted. The unreliability of so-called "tarnishing reactions" has been suggested.

Several examples of the use of punched cards in the identification of unknown minerals are presented. Their possible application to published descriptive data is indicated.

Two new mineral names are presented. A plea is made for the naming of distinctive microscopic minerals.

INTRODUCTION.

IT is becoming more and more apparent that variations in the physical properties of the ore minerals may impose very definite restrictions upon the use of conventional tables for their identification. Thus the unsuspected presence of isomorphous copper in more than one of a group of minerals may destroy the value of a microchemical test which may otherwise have been diagnostic. As the present knowledge of isomorphous relations is far from complete, an error of this type is well within the limits of probability. Tarnishing reactions can also be misleading.[2]

A punched card system similar to that developed by Donnay for the nonopaque minerals [3] (1) avoids several shortcomings of the conventional identification tables. Donnay's punched cards indicate the range of such quantitative data as the optical axial angle, thus the cards as punched represent an extension of quantitative data until they have become qualitative in nature. Inasmuch as this use of qualitative data functions successfully in the separation of nonopaque minerals, it should be no less successful in its application to the opaque and other ore minerals.[4] In testing the method, difficulty was encountered in the selection of determinative data which were both sufficiently diagnostic for the purpose and were generally available in the literature. Eventually it became necessary to make approximately 600 determinations of ore mineral properties in order to insure the production of a satisfactory set of cards.

[1] Published by permission of the Director, U. S. Bureau of Mines.

[2] Of 100 ore minerals selected alphabetically among the least rare species, a total of 111 variations in the tarnishing reactions were found upon comparing the data as given by Short with those of Farnham. (References 12 and 10 of bibliography.)

[3] Figures in parentheses refer to publications in the bibliography at the end of this report.

[4] Metallic to submetallic, opaque to nearly opaque minerals including a few associated with them such as nonopaque sphalerite.

Most geologists will agree that a detailed knowledge of mineral character has more than academic interest. Bateman (2), Gaudin (3), Head (4), Rasor (5), Schneiderhohn (6), Schwartz (7), among others, have made practical applcations to either ore dressing problems or economic geology. Other practical results might be expected to follow the use of the punched card method which, because of its inexpensive requirements, can be used anywhere.

With this identification aid, fewer ore minerals need be reported as "unknown," "unidentified" or "unnamed." It is the object of this paper to show that punched cards have very definite value in identification work especially where x-ray diffraction or other advanced methods are not available. Suggestions are offered for the preparation of a card set having diagnostic value.

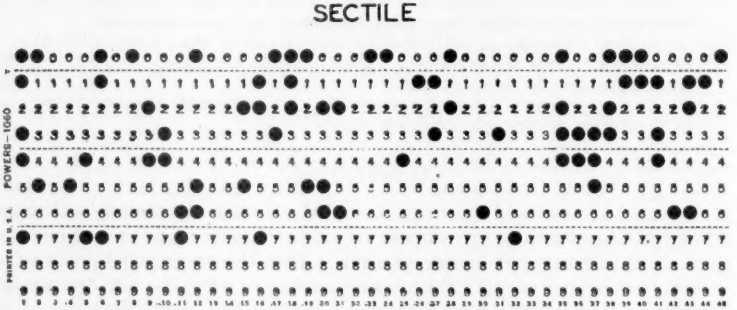

FIG. 1. Example of a tabulating card punched for determinative use.

PUNCHED CARDS.

The cards used by the writer are the tabulating machine type, $7\frac{3}{8}'' \times 3\frac{1}{4}''$, marked "Powers 1060." The card shown in Fig. 1 with pin-hole guides to facilitate use of a hand punch in punching out positions, was purchased from Remington-Rand, Inc., Washington, D. C. Only 356 of the total 450 positions of the cards were used to represent mineral species. This left unused positions for new species as soon as sufficient data become available. The mineral names represented by numerals on these cards are obtained by reference to an index containing a separate index card for each row of 45 punched card positions

The mineral properties listed below were selected by the writer and each assigned an individual card. A total of 117 punched cards constitute the completed set.

Color of polished surface (10 cards)
- White to grayish white.
- White, silver white, galena white.
- Grayish white.
- Gray.
- Definitely colored.
- Yellows, browns, cream, creamy.

Purple, purplish, reddish, lavender.
Pink.
Blue.
Color not available.

Cleavage: (5 cards)
Highly perfect to trace.
Perfect or nearly so.
Cleavage developed by etching.
Parting.
No cleavage found or not available.

Tenacity: (4 cards)
Brittle.
Sectile.
Not readily determined due to hardness.
Tenacity not available.

Optical: (8 cards)
Isotropic.
Anisotropic.
Anisotropism not available.
Opaque in fine powder.
Nonopaque in fine powder.
Reflectivity 20% or less (+ 5%).
Reflectivity 50% or more (− 5%).
Reflectivity not available.

Hardness: (14 cards)
Soft.
Hard.
$< 2, < 3, < 4, < 5, < 6, < 7, > 2, > 3, > 4, > 5, > 6, > 7.$

Tarnishing reactions: (11 cards)
HNO_3 effervesces.
HNO_3 positive reaction.
HNO_3 negative reaction.
HNO_3 reaction not available.
HCl effervesces.
HCl positive reaction.
HCl negative reaction.
HCl reaction not available.
KOH positive reaction.
KOH negative reaction.
KOH reaction not available.

Elements present: (51 cards)
Ag, Al, As, Au, Ba, Bi, Br, C, Ca, Cb (Nb), Cd, Ce, Cl, Co, CO_2, Cr, Cu, Fe, Ge, Hg, H_2O, I, Ir, K, Li, Mg, Mn, Mo, Na, Ni, Os, Pb, Pd, Pt, Rh, Ru, S, Sb, Se, Si, Sn, Ta, Te, Th, Ti, Tl, U, V, W, Zn, Zr.

Specific gravity: (14 cards)
< 3, 3–3.5, 3.5–4, 4–4.5, 5–5.5, 5.5–6, 6–6.5, 6.5–7, 7–7.5, 7.5–8, 8–9, > 9, not available.

DATA FOR PUNCHED CARDS.

Murdoch (8), Davy and Farnham (9), Farnham (10), Schneiderhohn and Ramdohr (11), and Short (12) have assembled data considered to have diagnostic value in the identification of ore minerals. Unfortunately certain etching or tarnishing tests adapted from the science of metallography, have been given an unjustifiable diagnostic status. A recent compilation of ore mineral properties is noteworthy for having completely ignored all of the so-called "tarnishing reactions" (13).

The conventional reactivity test is made by applying successively each reagent of a standard set.[5] Of the available reagents the two strong acids and KOH were selected by the writer as being the most satisfactory. Fewer variations were observed from KOH than with any other reagent.

Possible factors influencing reactivity include electrolytic effects, surface conditioning, and presence of catalytic agents introduced by polishing. The weaker electrolytes of the standard reagent set may by touching two dissimilar metallic minerals form an electrolytic cell (14). This may yield a tarnish that might not have been observed if strong acid had been used. It is possible that a "surface conditioning" may develop upon application of one of the reagents. A surface so affected may be rendered inert or reactive to the next reagent applied. Reactions that appear to result from a change in the order of applying the reagents may possibly be due to "surface conditioning."

Polished surfaces produced by mechanical methods develop a series of surface layers during the polishing. These layers consist of very small aggregates of micro-crystals of varying sizes, oxides of the metallic elements present in the minerals together with some of the polishing agent. As several of the polishing agents commonly employed are also known as catalytic agents, it is possible that they produce effects which are difficult to account for otherwise. Except for electrolytic effects, the formation of tarnish by other than chemical reaction is entirely hypothetical. Regardless of the exact nature of the reactions involved, the accumulated data indicate numerous positive and negative reactions for the same mineral species. These variations indicate that undue emphasis has been placed on the tarnishing reactions as an aid in ore mineral identification.

In order that microchemical tests, including the contact print method,[6] have maximum value an effort should be made to include all isomorphous elements in the composition cards. Thus the substitution of Co for Fe in danaite (cobaltian arsenopyrite), Co for Ni in willyamite (cobaltian ullmannite), As for Sb in a known variety of famatenite, and many other similar cases must be recognized in the punching out of the cards.

Color distinctions appear to be troublesome to many microscopists. In individual mineral species it may or may not show variations due to compositional changes. Apparently traces of Te in galena will change the color from "galena white" to a purple. It is obviously advisable to classify the colors of polished surfaces somewhat loosely. Thus all whites from pure white to grayish white can be indicated by three cards, "White to grayish white," "White" and "Grayish white." Distinctions have been made by others between white, silver white and galena white. Distinction is less difficult between "Grayish white" and "Gray," even so all border-line shades should be punched on both cards. More disagreement exists regarding definite color tints such as creamy, reddish or bluish. For doubtful cases a card, "Definitely colored," should be prepared.

[5] The standard set of reagents consists of HNO_3 1:1; HCl 1:1; KCN 20%; $FeCl_3$ 20%; $HgCl_2$ 5%; and KOH 40%.

[6] The contact print method of detecting chemical elements is to be recommended in obtaining data for use with the punched cards. See references 15 and 16 of bibliography.

Cleavage is troublesome. It is frequently missed especially in well-prepared sections. Older methods of polishing may develop cleavages difficult to find in carefully prepared sections. Sometimes cleavage is developed by etching. The broader pattern (microscopically) of parting should not be confused with cleavage. Many minerals known to have cleavage should also be included with those for which no cleavage is found, in preparing the punched cards.

The tenacity of microscopic mineral surfaces can be reported as either brittle or sectile. It would obviously be difficult to make any other distinction on a microscopical basis. A classification as either brittle or sectile is not a new one but has been the conventional procedure in the microscopical study of ore minerals. The method required for the use of the punched cards involves the application of a sharp needle to a polished mineral surface while under microscopic observation. If on being scratched, the mineral is found "cheese-like" and fails to yield a powder, the tenacity is considered to be sectile. Brittle minerals are those that under similar circumstances will be found to yield a powder. Fortunately few minerals are found to be "sectile, somewhat brittle" or "brittle, somewhat sectile."

Some minerals have been found to be both isotropic and anisotropic. Isotropic minerals may show weak anisotropic effects as the result of having been subjected to pressure. A surface may appear isotropic where the rotation of the plane of polarization obscures the anisotropic character until the upper nicol (analyzer) is rotated slightly.

It is advisable to make the opacity distinction a practical one. If the amount of light transmitted by an impalpable powder of the mineral is not of sufficient intensity to be of value in the determination of optical data, the mineral should be considered opaque. To make this test a small fragment of the mineral is ground as fine as possible in an agate mortar or at least until the grinding appears to be imperceptible. The powder is placed on an object glass immersed in a liquid and covered with a cover glass. It is examined microscopically with either a number 3 or 6 objective. Extremely fine particles may transmit light although the powder as a whole remains opaque. A mineral of this character can be considered opaque. Should transparent grains of a contaminating mineral be present, it is usually possible to distinguish between them and the host mineral. Opaque as used in the literature frequently refers to appearance in hand specimen or to relatively large fragments.

The ratio of light intensity as reflected from the polished specimen surface to the intensity of light vertically incident to that surface, known as the reflection percentage, has been determined for most of the ore minerals. The eye can readily distinguish low reflecting minerals such as bornite, cassiterite, covellite, tetrahedrite and uraninite from those of high reflectivity such as arsenopyrite, copper, gold, pyrite or silver. This fact has some diagnostic value if punched cards are prepared for ore minerals of low reflectivity (range about 10 to 25%) and for those of high reflectivity (range from about 50 to 97%). A separation can be made between these two groups by visual examination.

A sharp needle employed for hardness distinctions is bent at about a 45° angle 5 or 10 mm. from its point and mounted in a holder having an adjust-

able needle chuck. The hardness is obtained along with the tenacity during the same test. A distinction between "soft" and "hard" is a simple one providing the cards show an overlap as the boundary between the two classifications is approached. "Soft" minerals can be considered as those having a Mohs hardness between 1 and 4.5 and the "hard" greater than "4.5." With experience an ability can be developed which will permit the distinction within 1 or 2 positions of the Mohs scale of hardness. In order to anticipate this ability, cards should also be prepared on the basis of Mohs scale.

Specific gravity, rarely determined by microscopists, is usually available in the literature and is of considerable value in ore dressing. Its inclusion in the punched card set will be found useful in the comparison of published data.

Eventually the simple method of producing selective iridescent filming (17) (18) may be found to have considerable diagnostic value. A sufficient number of determinations have not been made to permit its use at present.

USE OF THE PUNCHED CARDS.

The following properties listed on the cards were determined for an unknown mineral as color (polished), white, perfect or nearly perfect cleavage, sectile, anisotropic, opaque, hardness between 1 to 4.5, reflectivity less than 50%, HNO_3 (+), HCl (−), and KOH (−). The punched cards for these properties, including trials using "not available" cards, indicate arsenic, eucairite, franckeite, guanajuatite, lengenbachite and petzite. Addition of the antimony card eliminates all but arsenic and franckeite. Arsenic is brittle, somewhat sectile, distinctly anisotropic with a reflectivity of 55. Franckeite is sectile not brittle, weakly anisotropic with a reflectivity of 36. The differences are sufficient to indicate franckeite.

Another unknown gave white, no cleavage, brittle, isotropic, opaque, soft, HNO_3 (+) and HCl (+). Proceeding as before schapbachite and galena are indicated. Schapbachite has no cleavage although it may show a lamellar structure that may be confused with cleavage, is brittle not sectile, contains bismuth and occurs in both isotropic and anisotropic forms. A test for bismuth can be made if it is considered necessary for verification of the schapbachite composition.

When applied to mineral properties as reported in the literature, sufficient data may or may not be found available to obtain results of value. Unsatisfactory results were obtained for an incompletely described mineral from Dracut, Massachusetts (19), although the tentative identification given as molybdenite would have received additional support if tenacity had been determined and found sectile.

Use of punched cards selected on the basis of published data gave the following suggestive results:

Benjaminite—possibly an argentian hammarite.
Cocinerite—possibly stromeyerite.
Hutchinsonite—possibly a thallian lengenbachite.
Von Diestite—tellurobismutite.
Weibullite—probably selenian galenobismutite.

Wolfachite—probably antimonian gersdorffite.
Wolfsbergite—chalcostibite.
New mineral (Cresson mine, Colo.) (20)—probably petzite.
New mineral (Leadville, Colo.) (21)—alpha-matildite (alpha-schapbachite).
Unidentified (Wentworth Centre, N. S.) (22)—valleriite.
Unidentified (Cashin mine, Colo.) (23)—valleriite.

NAMING THE MICROSCOPIC MINERALS.

Should a homogeneous mineral occurring in microscopic quantities receive a name and species rank if shown by the punched cards to be distinctive? Chemists of course would object to the use of a name except on the basis of a complete chemical analysis. However, many of their analyzed minerals never received a microscopic examination for homogeneity and were later discredited. If the determinative data are substantial, a name is certainly justified in spite of the inability to obtain a quantitative chemical analysis. It is doubtful if such minerals will later be discredited as frequently as those never checked for homogeneity.

A mineral formed as an oxidation product of altaite from the Organ Mountain mining district, New Mexico, can be cited as a homogeneous microscopic mineral unknown in larger quantities. As seen in polished sections, it is pale brown, sectile, anisotropic, contains Pb and Te and has a hardness of 1–2.[7] Its mode of formation suggests the possible formula $PbO \cdot TeO_2$ (?).

The writer proposes the name "Dunhamite" for this mineral first noted by K. C. Dunham (24).

The natural cadmium oxide, CdO, first found at Monte Poni, Sardinia, certainly deserves other than a chemical name. The euphonious "monteponite" is offered as a mineral name. The mineral, nearly opaque, is gray on polished surfaces, shows no cleavage, is brittle, somewhat sectile, reacts with both HNO_3 and HCl and has a hardness of 3.

The above minerals checked by the punched cards, appear unique. This check will frequently suggest an isomorphous variety rather than unique character. Both the homogeneity test—microscopical examination in polished section—and the punched card check are to be recommended in the identification of ore minerals.

TUSCALOOSA DIVISION, METALLURGICAL BRANCH,
U. S. BUREAU OF MINES, TUSCALOOSA, ALABAMA,
May 15, 1946.

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[7] The tarnishing reactions were determined as HNO_3. Instantly blackens followed by effervescence, developing a persistent structure; HCl (+); KCN practically (−); $FeCl_3$ (+) not persistent; $HgCl_2$ and KOH (−).

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REVIEWS*

What Industry Owes to Chemical Science—a Symposium. Arranged by R. B. PILCHER and FRANK B. JONES with fifty contributors. Pp. 372. Chemical Publishing Co., Brooklyn, N. Y., 1946. Price, $5.00.

Each part of the 18 chapters of this interesting book, which, by the way, is issued by authority of the Royal Institute of Chemistry, is written by an expert in the subject in non-technical language. The whole is an absorbing story of the contributions of chemical discoveries to the development of the various industries that serve mankind, minister to our comfort and necessities, and help raise our standard of living. It is not intended to be a technical treatise, although it does serve that purpose for technical students, but as general reading for all who enjoy good books.

The subject matter or some part of it has an appeal for everyone, since it covers such a wide range that some part of it deals with the daily homely matters of everyone's living. For example, here are some of the subjects covered; agriculture; foods, such as nutrition, bread, dairy products, fats, sugar, starch; water supplies and sanitation; pharmaceutical products; soaps; disinfectants; dye stuffs; textiles; paper and pulp; plastics; rubber; photography; chemicals; fuels; metals and minerals; building materials; transport.

He who wishes a good story can be satisfied; he who wishes technical information can obtain it.

The Geology of the Messina Copper Mines and Surrounding Country. P. G. SÖHNGE. Pp. 280; pls. 73; figs. 22. Union of S. Africa, Geol. Surv. Mem. 40, Pretoria, 1945 (1946). Price £1. 1s.

This memoir covers an area and a group of copper deposits of great interest to economic geologists. The region is underlain by an Archean complex of metamorphic rocks derived from both sedimentary and igneous rocks. A separate chapter on the processes of their metamorphism follows one on their description. These metamorphic rocks are cut by pre-Cambrian (?) granitic rocks, followed by mafic intrusives of pre-Karroo age and are overlain by members of the Karroo.

The copper lodes are described in detail with attention to minute details of structure mineralogy and mineral distribution. The replacement lodes are localized along the Messina Fault-Fissure zone and consist of fissures, brecciated areas and pipes. Pronounced zoning occurs with a central zone of quartz zoisite, epidote, chalcopyrite; an intermediate zone with prehnite, sericite, zoisite and considerable bornite; and an outer and shallow zone with chalcocite dominant. Hematite, hydrothermal feldspar and garnet occur.

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

BOOKS RECEIVED.

A. T. BRODERICK.

Flourspar Deposits of the Jamestown District, Boulder County, Colorado. E. N. GODDARD. Pp. 47; pls. 11; figs. 2. Colorado Scientific Society Proceedings, Vol. 15, No. 1. Denver, Colorado, 1946. *Total indicated and inferred ore—645,000 tons 60% CaF_2, 330,000 tons 30% CaF_2.*

Lee County Mineral Resources. F. E. VESTAL. Pp. 135; ills. 19; pls. 3. Mississippi State Geol. Survey. Bul. 63. University, 1946. *Area contains a potential oil structure, ample unexploited deposits amenable to rockwool, portland cement manufacture.*

The Northeastern Portion of the Timigami Lake Area. W. W. MOORHOUSE. Pp. 46, photos 13, ills. 10, map. Ontario Dept. of Mines. Vol. 51, Part 6. Toronto, 1946. *Numerous small showings of Fe, Ni, Cu, Mo, Pyrite, As, Au, Ag.*

A Geochemical Survey of the Underground Water Supplies of the Union of South Africa. G. W. BOND. Pp. 208. Maps 2. Union of S. Africa Geol. Surv. Mem. 41. Pretoria, 1946. *Suggests ground water character-rock formation correlation.*

Publications on the Geology and Mineral Resources of Virginia. A. BEVAN. Pp. 6. Virginia Geological Survey, Circ. 2, Supp. 1. University, 1946.

Map Showing Principal Mineral Deposits in the State of Oregon. Dept. of Geol. & Mineral Inds. of the State of Oregon. 20″ × 26″. Scale 1 : 1,000,000 1946.

Middle East Science. E. B. WORTHINGTON. Pp. 239; photos 16; maps 5. London, 1946. *Problems related to the non-agricultural resources including water resources, and problems with a biological basis affecting population.*

The Agricultural Development of the Middle East. B. A. KEEN. Pp. 126; pls. 32; map 1. London, 1946.

Ontario Dept. of Mines, Annual Report. Vol. 52, Part 1, 1943. Toronto, 1946. Statistical Review of the Mineral Industry of Ontario for 1942; List of Mines, Quarries, and Works; Mines of Ontario; Mining Accidents. Pp. 277.

Le Charbon. AUGUSTIN LOMBARD. Pp. 278; tabls. 1; figs. 65; pls. 6. Lausanne, 1946. *A comprehensive text covering history of coal, geology, constitution, classification, methods of investigation, structural features, flora, formation of coals, descriptions of important world coal basins; exploitation of coal, and applications.*

SCIENTIFIC NOTES AND NEWS

FREDERICK M. SWAIN of Pennsylvania State College was recently appointed Assistant Professor in the Department of Geology and Mineralogy of the University of Minnesota. He will teach petroleum geology and micropaleontology.

JOE WEBB PEOPLES has returned from the U. S. Geological Survey to the Department of Geology, Wesleyan University, Middletown, Connecticut.

F. H. FITCH has left for Perak to rejoin the Geological Survey in Malaya.

A. K. SNELGROVE, visiting professor of geology at Rutgers University for 1945–46, has returned to his post as head of the department of geological engineering at the Michigan College of Mining and Technology, Houghton, from which he has been on leave of absence to enable him to initiate at Rutgers a new Bureau of Mineral Research, with particular attention to undeveloped feldspar and agricultural mineral resources in New Jersey and new mineralogical and mineral dressing data for the glass sand industry of the state. During the past summer Dr. Snelgrove, as consulting geologist to the Geological Survey of Newfoundland, supervised the work of ten field parties in the island and inspected exploration work being conducted by companies in the Labrador iron trough.

L. R. WILSON has recently gone to Massachusetts State College at Amherst to take Dr. Gordon's place upon the latter's retirement.

CARL TOLMAN, until recently head of the geology department at Washington University, has been made acting dean of the School of Graduate Studies there.

F. S. TURNEAURE who has been visiting lecturer in geology at Harvard this summer has returned to Oruro, Bolivia, where he is consulting geologist for M. Hochschild, S.A.M.I.

R. A. SMITH has retired as State Geologist of Michigan after 27 years of service. Gerald E. Eddy, who has been with the State Geological Survey since 1933, was appointed to succeed him.

FRANK W. DEWOLF has been made professor of geology emeritus since his retirement on September 1 as professor of geology and head of the department of geology at the University of Illinois.

PAUL M. TYLER has taken over the duties of executive officer for Massachusetts Institute of Technology Metallurgical Laboratories, Watertown, Mass. He returned from Europe last spring, where he reported investigations on metals and minerals in Germany for the Department of Commerce.

DEAN FRASCHE has returned from Australia and has gone to Manila.

GEORGE H. ASHLEY, chief of the Pennsylvania Bureau of Topographic and Geologic Survey, retired August 31. He is succeeded by Dr. Ralph W. Stone, who will serve from September 1 of the current year to December 31, at which time he also will retire. Dr. Ashley is 81 and Dr. Stone will be 70 next November.

S. H. DOLBEAR is doing consulting work in China for the Chinese Government.

CARLOS PARADISI has been appointed Director of Mines for Venezuela to succeed J. Car-Denas Varela, who has been transferred to the Banco Obrero. Dr. Paradisi obtained his technical training in Chile and on his return to Venezuela was for some time attached to the Servicio Tecnico de Mineria y Geologie of the Ministerio de Fomento.

R. B. LADOO, specialist in non-metallic minerals, during the past summer studied the possibilities of establishing an artificial abrasives manufacturing industry in the Portland, Oregon, area.

ROBERT M. DREYER is now associate professor of geology at the University of Kansas.

W. W. BRADLEY has resigned as California state mineralogist, a post he has held for the last eighteen years. W. B. Tucker, Los Angeles district mining engineer, has been appointed his successor temporarily, pending selection of a permanent mineralogist through a civil service examination.

ARTHUR YATES returned to New York last July after completing the examination and sampling of the nickeliferous deposits in the states of Aragua, Miranda and Cojedes for the International Nickel Company in Venezuela.

T. L. JOHNSTON returned in August from Japan where he spent six months with the mining and geological division of natural resources, GHQ, SCAP.

SCHIOU CHUAN SUN is now assistant professor in mineral engineering at Pennsylvania State College, State College, Pennsylvania.

CARL ZAPFFE, manager of iron ore properties for the Northern Pacific Railway Co., has been appointed Brainerd, Minnesota, Community chairman of the Committee for Economic Development.

Formation of a sand division within the American Foundrymen's Association, technical society of the castings industry, has been announced by S. C. Massari, technical director. The new division is an outgrowth of the organization's sand research project started in 1921. Chairman of the division is Dr. H. Ries; vice chairman, P. E. Kyle; temporary secretary H. F. Scovie. Any interested AFA member may register for membership in the new division.

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